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(54) Device for improving cardiac function in heart failure or CHF patients

(57) A device for decreasing workload, maintaining or increasing cardiac output and/or achieving a desirable autonomic balance by stimulating one or more par-

asympathetic nerves. One or more stimulation pulses is delivered postinspiration, and is based at least in part on the detection of one or more cardiac event.

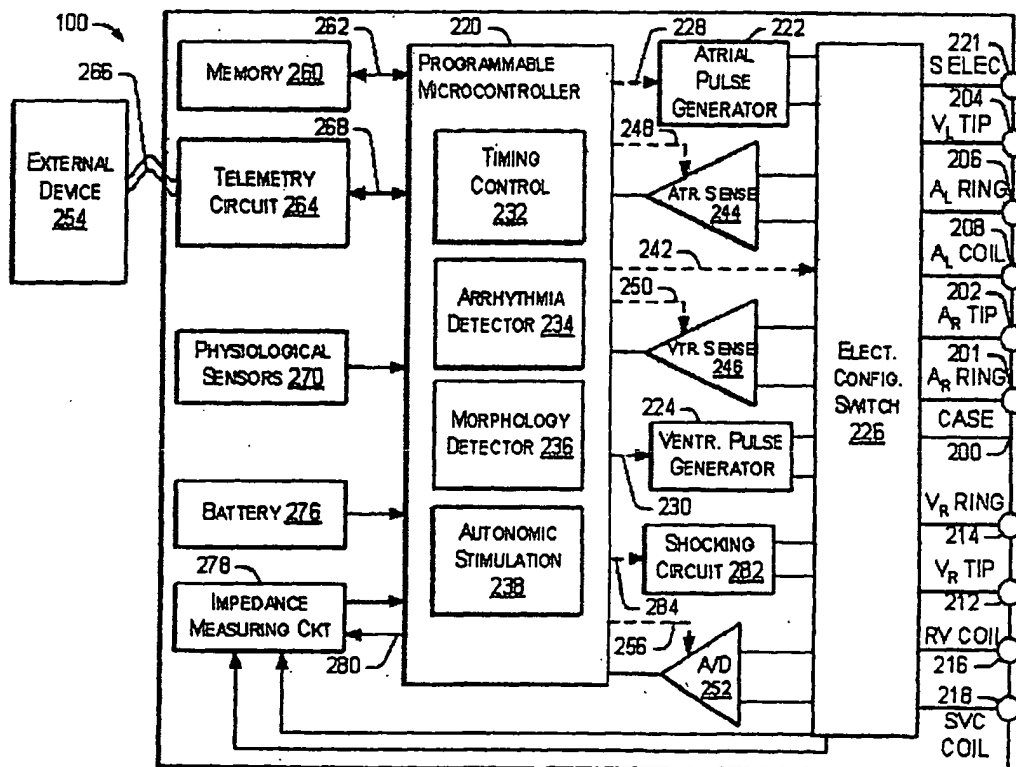


Fig. 2

## Description

**[0001]** The present invention generally relates to cardiac pacing and/or stimulation therapy. In particular it is concerned with stimulating parasympathetic nerves in a patient experiencing, or at risk of experiencing, congestive heart failure.

**[0002]** Congestive heart failure (CHF) is a condition that is often associated with a weakened heart that cannot pump enough blood to body organs. In CHF, the heart may be weakened due to hypertension, vascular disease, valvular disease, etc. Or, CHF may cause a fluid or chemical imbalance that leads to such diseases. In either case, once a patient is diagnosed with CHF, the disease typically worsens with time. CHF patients often have elevated heart rates, which may be considered a natural physiologic response to maintain or increase cardiac output. Cardiac output may be determined by multiplying stroke volume by heart rate. Hence an increase in heart rate may increase cardiac output. However, an increase in heart rate may be detrimental to a diseased heart. In particular, the condition of a diseased heart typically worsens in response to an increase in heart rate. Thus, to maintain or increase cardiac output, most agree that an increase in stroke volume is preferable to an increase in heart rate.

**[0003]** Traditional implantable pacing devices are often indicated for CHF patients. Such devices typically aim to compensate for CHF by maintaining a suitable heart rate; however, a controlled heart rate alone may do little to slow progression of CHF. Consequently, a need exists for devices that can better address cardiac output issues, particularly in CHF patients. As discussed below, stimulation of parasympathetic nerves can help to address such cardiac output issues.

**[0004]** According to one aspect of the invention, there is provided apparatus for improving heart performance, comprising: means for detecting a need for increased cardiac output; and stimulating means responsive to the detecting, means characterised in that the stimulating means comprises means for stimulating a parasympathetic nerve, to increase vagal tone and to increase end diastolic volume.

**[0005]** Preferably, the means for detecting comprises one or more sensors. Preferably, the stimulating means comprises an electrode positionable proximate to the parasympathetic nerve.

**[0006]** According to another aspect of the invention, there is provided apparatus for improving heart performance, comprising: means for detecting a need for increased cardiac output and stimulating means responsive to the detecting, characterised in that the means for detecting is arranged to detect a need to increase stroke volume; the stimulating means is arranged to stimulate a parasympathetic nerve, responsive to the detecting, according to one or more stimulation parameters to increase vagal tone and thereby to increase end diastolic volume; the apparatus also comprising means for de-

termining whether adequate AV conduction exist, and means adjusting one or more of the stimulation parameters responsive to the determining.

**[0007]** The invention also extends to apparatus for improving heart performance, characterised by: means for detecting an increase in sympathetic tone; means for stimulating a parasympathetic nerve according to one or more stimulation parameters; means for determining whether adequate AV conduction exists; and means for implementing ventricular pacing if inadequate AV conduction exists.

**[0008]** Thus, the invention is concerned with systems for decreasing workload, maintaining or increasing cardiac output and/or achieving a desirable autonomic balance by stimulating one or more parasympathetic nerves. Various exemplary systems provide for delivering one or more stimulation pulses postinspiration, based at least in part on detection of one or more cardiac event and/or during a refractory period. Other exemplary methods and/or devices are also disclosed. The various exemplary systems and/or devices described herein are suitable for use in a variety of pacing therapies and other cardiac related therapies.

**[0009]** The invention enables a method comprising: detecting a need for increased cardiac output; and responsive to detecting the need for increased cardiac output, stimulating a parasympathetic nerve to increase vagal tone and increase end diastolic volume.

**[0010]** Preferably, the detecting comprises sensing a pressure and preferably the stimulating occurs postinspiration only. Preferably, detection of a cardiac event initiates the stimulating. Preferably, the invention permits synchronizing the stimulating to one or more events in a cardiac cycle.

**[0011]** Preferably, the stimulation halts after a set period of time. After halting stimulation a diagnostic algorithm may be implemented. Then, the results of the diagnostic algorithm after the halting may be compared to results acquired prior to the stimulating.

**[0012]** The invention also enables a method comprising: detecting a need to increase stroke volume; responsive to the detecting, stimulating a parasympathetic nerve according to one or more stimulation parameters to increase vagal tone and increase end diastolic volume; determining whether adequate AV conduction exists; and responsive to the determining, adjusting one or more of the one or more stimulation parameters.

**[0013]** Preferably it is arranged to determine whether stroke volume increased. Preferably, one or more of the stimulation parameters is adjusted in response to an inadequate increase in stroke volume. Preferably, the detection comprises detecting a need to increase cardiac output, and/or a need to reduce workload, and/or a need to reduce sympathetic tone or to increase parasympathetic tone.

**[0014]** Again, preferably, stimulation occurs postinspiration only, and detection of a cardiac event initiates the stimulation.

**[0015]** The invention also enables a method comprising: detecting an increase in sympathetic tone; responsive to the detecting, stimulating a parasympathetic nerve according to one or more stimulation parameters; determining whether adequate AV conduction exists; and responsive to the determining, implementing ventricular pacing if inadequate AV conduction exists.

**[0016]** Preferably, it is arranged to determine whether a decrease has occurred in sympathetic tone. Preferably, one or more of the stimulation parameters is adjusted in response to an inadequate decrease in sympathetic tone. Again, preferably, stimulation occurs postinspiration only, and detection of a cardiac event initiates the stimulation.

**[0017]** The invention also enables a method comprising: detecting a heart rate above a threshold rate; stimulating a parasympathetic nerve to increase vagal tone; and pacing one or more chambers of the heart at a rate less than the threshold rate, and preferably, synchronizing the stimulating with one or more events in a cardiac cycle.

**[0018]** The invention may be carried into practice in various ways and some embodiments will now be described by way of example, with reference to the accompanying drawings.

**[0019]** Fig. 1 is a simplified diagram illustrating an exemplary implantable stimulation device in electrical communication with at least three leads implanted into a patient's heart and at least one other lead for delivering stimulation and/or shock therapy.

**[0020]** Fig. 2 is a functional block diagram of an exemplary implantable stimulation device illustrating basic elements that are configured to provide cardioversion, defibrillation, pacing stimulation and/or autonomic nerve stimulation. The implantable stimulation device is further configured to sense information and administer stimulation pulses responsive to such information.

**[0021]** Fig. 3 is a simplified approximate anatomical diagram of a parasympathetic pathway and a sympathetic pathway of the autonomic nervous system.

**[0022]** Fig. 4 is a simplified approximate anatomical diagram of sympathetic pathways and/or parasympathetic pathways to the heart.

**[0023]** Fig. 5 is a simplified approximate anatomical diagram of parasympathetic afferent pathways.

**[0024]** Fig. 6 is an approximate anatomical ventral view diagram of a human heart including some arteries, veins and nerves.

**[0025]** Fig. 7 is an approximate anatomical dorsal view diagram of a human heart including some arteries, veins and nerves.

**[0026]** Fig. 8 is a block diagram of an exemplary method for responding to a need for increased cardiac output.

**[0027]** Fig. 9 is a block diagram of an exemplary method for responding to an increase in sympathetic activity.

**[0028]** Fig. 10 is a block diagram of an exemplary method for compensating for inadequate AV conduction.

**[0029]** Fig. 11 is an approximate anatomical ventral view diagram of a human heart including some arteries, veins and nerves and stimulation leads associated with a pacing device.

**[0030]** Fig. 12 is a block diagram of an exemplary method for delivering a stimulation pulse postinspiration.

**[0031]** Fig. 13 is a block diagram of an exemplary method for delivering parasympathetic stimulation during a postinspiration phase and/or based on detection of one or more cardiac events.

#### Overview

**[0032]** Various exemplary methods and/or devices described herein stimulate a parasympathetic pathway in an effort to maintain or increase cardiac output and/or to achieve a desirable autonomic balance. The description that follows introduces an implantable stimulation device suitable for use with various exemplary methods. Of course, other suitable implantable devices may be used. In addition, the description includes a discussion of physiological conditions related to cardiac output and/or CHF, which also discusses parasympathetic and sympathetic concerns. Next, physiology of the autonomic system is presented, followed by a presentation of various exemplary methods and/or devices that rely on autonomic stimulation to, at least in part, maintain or increase cardiac output and/or achieve a desirable autonomic balance. Various exemplary methods may deliver parasympathetic stimulation postinspiration and/or in synchrony with various aspects of a cardiac cycle.

#### Exemplary Stimulation Device

**[0033]** The techniques described below are intended to be implemented in connection with any stimulation device that is configured or configurable to stimulate nerves and/or stimulate and/or shock a patient's heart.

**[0034]** Fig. 1 shows an exemplary stimulation device 100 in electrical communication with a patient's heart 102 by way of three leads 104, 106, 108, suitable for delivering multi-chamber stimulation and shock therapy.

The leads 104, 106, 108 are optionally configurable for delivery of stimulation pulses suitable for stimulation of autonomic nerves. In addition, the device 100 includes a fourth lead 110 having, in this implementation, three electrodes 144, 144', 144" suitable for stimulation of autonomic nerves. This lead may be positioned in and/or near a patient's heart or near an autonomic nerve within a patient's body and remote from the heart. The right atrial lead 104, as the name implies, is positioned in and/or passes through a patient's right atrium. The right atrial lead 104 optionally senses atrial cardiac signals and/or provide right atrial chamber stimulation therapy. As shown in Fig. 1, the stimulation device 100 is coupled to an implantable right atrial lead 104 having, for exam-

ple, an atrial tip electrode 120, which typically is implanted in the patient's right atrial appendage. The lead 104, as shown in Fig. 1, also includes an atrial ring electrode 121. Of course, the lead 104 may have other electrodes as well. For example, the right atrial lead optionally includes a distal bifurcation having electrodes suitable for stimulation of autonomic nerves.

**[0035]** To sense atrial cardiac signals, ventricular cardiac signals and/or to provide chamber pacing therapy, particularly on the left side of a patient's heart, the stimulation device 100 is coupled to a coronary sinus lead 106 designed for placement in the coronary sinus and/or tributary veins of the coronary sinus. Thus, the coronary sinus lead 106 is optionally suitable for positioning at least one distal electrode adjacent to the left ventricle and/or additional electrode(s) adjacent to the left atrium. In a normal heart, tributary veins of the coronary sinus include, but may not be limited to, the great cardiac vein, the left marginal vein, the left posterior ventricular vein, the middle cardiac vein, and the small cardiac vein.

**[0036]** Accordingly, an exemplary coronary sinus lead 106 is optionally designed to receive atrial and ventricular cardiac signals and to deliver left ventricular pacing therapy using, for example, at least a left ventricular tip electrode 122, left atrial pacing therapy using at least a left atrial ring electrode 124, and shocking therapy using at least a left atrial coil electrode 126. For a complete description of a coronary sinus lead, the reader is directed to U.S. Patent Application No. 09/457,277, filed 12/8/99, entitled "A Self-Anchoring, Steerable Coronary Sinus Lead" (Pianca et al.); and U.S. Patent No. 5,466,254, "Coronary Sinus Lead with Atrial Sensing Capability" (Helland). The coronary sinus lead 106 further optionally includes electrodes for stimulation of autonomic nerves. Such a lead may include pacing and autonomic nerve stimulation functionality and may further include bifurcations or legs. For example, an exemplary coronary sinus lead includes pacing electrodes capable of delivering pacing pulses to a patient's left ventricle and at least one electrode capable of stimulating an autonomic nerve. An exemplary coronary sinus lead (or left ventricular lead or left atrial lead) may also include at least one electrode capable of stimulating an autonomic nerve, such an electrode may be positioned on the lead or a bifurcation or leg of the lead.

**[0037]** Stimulation device 100 is also shown in electrical communication with the patient's heart 102 by way of an implantable right ventricular lead 108 having, in this exemplary implementation, a right ventricular tip electrode 128, a right ventricular ring electrode 130, a right ventricular (RV) coil electrode 132, and an SVC coil electrode 134. Typically, the right ventricular lead 108 is transvenously inserted into the heart 102 to place the right ventricular tip electrode 128 in the right ventricular apex so that the RV coil electrode 132 will be positioned in the right ventricle and the SVC coil electrode 134 will be positioned in the superior vena cava. Accordingly, the right ventricular lead 108 is capable of sensing or receiving

cardiac signals, and delivering stimulation in the form of pacing and shock therapy to the right ventricle. An exemplary right ventricular lead may also include at least one electrode capable of stimulating an autonomic nerve, such an electrode may be positioned on the lead or a bifurcation or leg of the lead.

**[0038]** Fig. 2 shows an exemplary, simplified block diagram depicting various components of stimulation device 100. The stimulation device 100 can be capable of treating both fast and slow arrhythmias with stimulation therapy, including cardioversion, defibrillation, and pacing stimulation. The stimulation device can be solely or further capable of delivering stimuli to autonomic nerves. While a particular multi-chamber device is shown, it is to be appreciated and understood that this is done for illustration purposes only. Thus, the techniques and methods described below can be implemented in connection with any suitably configured or configurable stimulation device. Accordingly, one of skill in the art could readily duplicate, eliminate, or disable the appropriate circuitry in any desired combination to provide a device capable of treating the appropriate chamber(s) or regions of a patient's heart with cardioversion, defibrillation, pacing stimulation, and/or autonomic nerve stimulation.

**[0039]** Housing 200 for stimulation device 100 is often referred to as the "can", "case" or "case electrode", and may be programmably selected to act as the return electrode for all "unipolar" modes. Housing 200 may further be used as a return electrode alone or in combination with one or more of the coil electrodes 126, 132 and 134 for shocking purposes. Housing 200 further includes a connector (not shown) having a plurality of terminals 201, 202, 204, 206, 208, 212, 214, 216, 218, 221 (shown schematically and, for convenience, the names of the electrodes to which they are connected are shown next to the terminals).

**[0040]** To achieve right atrial sensing, pacing and/or autonomic stimulation, the connector includes at least a right atrial tip terminal ( $A_R$  TIP) 202 adapted for connection to the atrial tip electrode 120. A right atrial ring terminal ( $A_R$  RING) 201 is also shown, which is adapted for connection to the atrial ring electrode 121. To achieve left chamber sensing, pacing, shocking, and/or autonomic stimulation, the connector includes at least a left ventricular tip terminal ( $V_L$  TIP) 204, a left atrial ring terminal ( $A_L$  RING) 206, and a left atrial shocking terminal ( $A_L$  COIL) 208, which are adapted for connection to the left ventricular tip electrode 122, the left atrial ring electrode 124, and the left atrial coil electrode 126, respectively. Connection to suitable autonomic nerve stimulation electrodes is also possible via these and/or other terminals (e.g., via a nerve stimulation terminal S ELEC 221).

**[0041]** To support right chamber sensing, pacing, shocking, and/or autonomic nerve stimulation, the connector further includes a right ventricular tip terminal ( $V_R$  TIP) 212, a right ventricular ring terminal ( $V_R$  RING) 214,

a right ventricular shocking terminal (RV COIL) 216, and a superior vena cava shocking terminal (SVC COIL) 218, which are adapted for connection to the right ventricular tip electrode 128, right ventricular ring electrode 130, the RV coil electrode 132, and the SVC coil electrode 134, respectively. Connection to suitable autonomic nerve stimulation electrodes is also possible via these and/or other terminals (e.g., via the nerve stimulation terminal S ELEC 221).

[0042] At the core of the stimulation device 100 is a programmable microcontroller 220 that controls the various modes of stimulation therapy. As is well known in the art, microcontroller 220 typically includes a microprocessor, or equivalent control circuitry, designed specifically for controlling the delivery of stimulation therapy, and may further include RAM or ROM memory, logic and timing circuitry, state machine circuitry, and I/O circuitry. Typically, microcontroller 220 includes the ability to process or monitor input signals (data or information) as controlled by a program code stored in a designated block of memory. The type of microcontroller is not critical to the described implementations. Rather, any suitable microcontroller 220 may be used that carries out the functions described herein. The use of microprocessor-based control circuits for performing timing and data analysis functions are well known in the art.

[0043] Representative types of control circuitry that may be used in connection with the described embodiments can include the microprocessor-based control system of U.S. Patent No. 4,940,052 (Mann et al.), the state-machine of U.S. Patent Nos. 4,712,555 (Thornander et al.) and 4,944,298 (Sholder). For a more detailed description of the various timing intervals used within the stimulation device and their interrelationship, see U.S. Patent 4,788,980 (Mann et al.).

[0044] Fig. 2 also shows an atrial pulse generator 222 and a ventricular pulse generator 224 that generate pacing stimulation pulses for delivery by the right atrial lead 104, the coronary sinus lead 106, and/or the right ventricular lead 108 via an electrode configuration switch 226. It is understood that in order to provide stimulation therapy in each of the four chambers of the heart (or to autonomic nerves) the atrial and ventricular pulse generators, 222 and 224, may include dedicated, independent pulse generators, multiplexed pulse generators, or shared pulse generators.

The pulse generators 222 and 224 are controlled by the microcontroller 220 via appropriate control signals 228 and 230, respectively, to trigger or inhibit the stimulation pulses.

[0045] Microcontroller 220 further includes timing control circuitry 232 to control the timing of the stimulation pulses (e.g., pacing rate, atrio-ventricular (AV) delay, atrial interconduction (A-A) delay, or ventricular interconduction (V-V) delay, etc.) as well as to keep track of the timing of refractory periods, blanking intervals, noise detection windows, evoked response windows, alert intervals, marker channel timing, etc., which is well

known in the art.

[0046] Microcontroller 220 further includes an arrhythmia detector 234, a morphology detector 236, and optionally an orthostatic compensator and a minute ventilation (MV) response module, the latter two are not shown in Fig. 2. These components can be utilized by the stimulation device 100 for determining desirable times to administer various therapies, including those to reduce the effects of orthostatic hypotension. The aforementioned components may be implemented in hardware as part of the microcontroller 220, or as software/firmware instructions programmed into the device and executed on the microcontroller 220 during certain modes of operation.

[0047] Microcontroller 220 further includes an autonomic nerve stimulation module 238 for performing a variety of tasks related to autonomic nerve stimulation. This component can be utilized by the stimulation device 100 for determining desirable times to administer various therapies, including, but not limited to, parasympathetic stimulation. The autonomic module 238 may be implemented in hardware as part of the microcontroller 220, or as software/firmware instructions programmed into the device and executed on the microcontroller 220 during certain modes of operation.

[0048] The electronic configuration switch 226 includes a plurality of switches for connecting the desired electrodes to the appropriate I/O circuits, thereby providing complete electrode programmability. Accordingly, switch 226, in response to a control signal 242 from the microcontroller 220, determines the polarity of the stimulation pulses (e.g., unipolar, bipolar, combipolar, etc.) by selectively closing the appropriate combination of switches (not shown) as is known in the art.

[0049] Atrial sensing circuits 244 and ventricular sensing circuits 246 may also be selectively coupled to the right atrial lead 104, coronary sinus lead 106, and the right ventricular lead 108, through the switch 226 for detecting the presence of cardiac activity in each of the four chambers of the heart. Accordingly, the atrial (ATR. SENSE) and ventricular (VTR. SENSE) sensing circuits, 244 and 246, may include dedicated sense amplifiers, multiplexed amplifiers, or shared amplifiers. Switch 226 determines the "sensing polarity" of the cardiac signal by selectively closing the appropriate switches, as is also known in the art. In this way, the clinician may program the sensing polarity independent of the stimulation polarity. The sensing circuits (e.g., 244 and 246) are optionally capable of obtaining information indicative of tissue capture.

[0050] Each sensing circuit 244 and 246 preferably employs one or more low power, precision amplifiers with programmable gain and/or automatic gain control, bandpass filtering, and a threshold detection circuit, as known in the art, to selectively sense the cardiac signal of interest. The automatic gain control enables the device 100 to deal effectively with the difficult problem of sensing the low amplitude signal characteristics of atrial

or ventricular fibrillation.

**[0051]** The outputs of the atrial and ventricular sensing circuits 244 and 246 are connected to the microcontroller 220, which, in turn, is able to trigger or inhibit the atrial and ventricular pulse generators 222 and 224, respectively, in a demand fashion in response to the absence or presence of cardiac activity in the appropriate chambers of the heart. Furthermore, as described herein, the microcontroller 220 is also capable of analyzing information output from the sensing circuits 244 and 246 and/or the data acquisition system 252 to determine or detect whether and to what degree tissue capture has occurred and to program a pulse, or pulses, in response to such determinations. The sensing circuits 244 and 246, in turn, receive control signals over signal lines 248 and 250 from the microcontroller 220 for purposes of controlling the gain, threshold, polarization charge removal circuitry (not shown), and the timing of any blocking circuitry (not shown) coupled to the inputs of the sensing circuits, 244 and 246, as is known in the art.

**[0052]** For arrhythmia detection, the device 100 utilizes the atrial and ventricular sensing circuits, 244 and 246, to sense cardiac signals to determine whether a rhythm is physiologic or pathologic. In reference to arrhythmias, as used herein, "sensing" is reserved for the noting of an electrical signal or obtaining data (information), and "detection" is the processing (analysis) of these sensed signals and noting the presence of an arrhythmia. The timing intervals between sensed events (e.g., P-waves, R-waves, and depolarization signals associated with fibrillation which are sometimes referred to as "F-waves" or "Fib-waves") are then classified by the arrhythmia detector 234 of the microcontroller 220 by comparing them to a predefined rate zone limit (i.e., bradycardia, normal, low rate VT, high rate VT, and fibrillation rate zones) and various other characteristics (e.g., sudden onset, stability, physiologic sensors, and morphology, etc.) in order to determine the type of remedial therapy that is needed (e.g., bradycardia pacing, anti-tachycardia pacing, cardioversion shocks or defibrillation shocks, collectively referred to as "tiered therapy").

**[0053]** Cardiac signals are also applied to inputs of an analog-to-digital (A/D) data acquisition system 252. The data acquisition system 252 is configured to acquire intracardiac electrogram signals, convert the raw analog data into a digital signal, and store the digital signals for later processing and/or telemetric transmission to an external device 254. The data acquisition system 252 is coupled to the right atrial lead 104, the coronary sinus lead 106, the right ventricular lead 108 and/or the nerve stimulation lead through the switch 226 to sample cardiac signals across any pair of desired electrodes.

**[0054]** The microcontroller 220 is further coupled to a memory 260 by a suitable data/address bus 262, wherein the programmable operating parameters used by the microcontroller 220 are stored and modified, as required, in order to customize the operation of the stim-

ulation device 100 to suit the needs of a particular patient. Such operating parameters define, for example, pacing pulse amplitude, pulse duration, electrode polarity, rate, sensitivity, automatic features, arrhythmia detection criteria, and the amplitude, waveshape, number of pulses, and vector of each shocking pulse to be delivered to the patient's heart 102 within each respective tier of therapy. One feature of the described embodiments is the ability to sense and store a relatively large amount of data (e.g., from the data acquisition system 252), which data may then be used for subsequent analysis to guide the programming of the device.

**[0055]** Advantageously, the operating parameters of the implantable device 100 may be non-invasively programmed into the memory 260 through a telemetry circuit 264 in telemetric communication via communication link 266 with the external device 254, such as a programmer, transtelephonic transceiver, or a diagnostic system analyzer. The microcontroller 220 activates the telemetry circuit 264 with a control signal 268. The telemetry circuit 264 advantageously allows intracardiac electrograms and status information relating to the operation of the device 100 (as contained in the microcontroller 220 or memory 260) to be sent to the external device 254 through an established communication link 266.

**[0056]** The stimulation device 100 can further include a physiologic sensor 270, commonly referred to as a "rate-responsive" sensor because it is typically used to adjust pacing stimulation rate according to the exercise state of the patient. However, the physiological sensor 270 may further be used to detect changes in cardiac output (see, e.g., U.S. Pat. No. 6,314,323, entitled "Heart stimulator determining cardiac output, by measuring the systolic pressure, for controlling the stimulation", to Ekwall, issued November 6, 2001, which discusses a pressure sensor adapted to sense pressure in a right ventricle and to generate an electrical pressure signal corresponding to the sensed pressure, an integrator supplied with the pressure signal which integrates the pressure signal between a start time and a stop time to produce an integration result that corresponds to cardiac output), changes in the physiological condition of the heart, or diurnal changes in activity (e.g., detecting sleep and wake states). Accordingly, the microcontroller 220 responds by adjusting the various pacing parameters (such as rate, AV Delay, V-V Delay, etc.) at which the atrial and ventricular pulse generators, 222 and 224, generate stimulation pulses.

**[0057]** While shown as being included within the stimulation device 100, it is to be understood that the physiologic sensor 270 may also be external to the stimulation device 100, yet still be implanted within or carried by the patient. Examples of physiologic sensors that may be implemented in device 100 include known sensors that, for example, sense respiration rate, pH of blood, ventricular gradient, cardiac output, preload, afterload, workload, contractility, and so forth. Another

sensor that may be used is one that detects activity variance, wherein an activity sensor is monitored diurnally to detect the low variance in the measurement corresponding to the sleep state. For a complete description of the activity variance sensor, the reader is directed to U.S. Patent No. 5,476,483 (Bornzin et al.), issued 12/19/1995, which patent is hereby incorporated by reference.

**[0058]** More specifically, the physiological sensors 270 optionally include sensors for detecting movement and minute ventilation in the patient. The physiological sensors 270 may include a position sensor and/or a minute ventilation (MV) sensor to sense minute ventilation, which is defined as the total volume of air that moves in and out of a patient's lungs in a minute. Signals generated by the position sensor and MV sensor are passed to the microcontroller 220 for analysis in determining whether to adjust the pacing rate, etc. The microcontroller 220 monitors the signals for indications of the patient's position and activity status, such as whether the patient is climbing upstairs or descending downstairs or whether the patient is sitting up after lying down.

**[0059]** The stimulation device additionally includes a battery 276 that provides operating power to all of the circuits shown in Fig. 2. For the stimulation device 100, which employs shocking therapy, the battery 276 is capable of operating at low current drains for long periods of time (e.g., preferably less than 10  $\mu$ A), and is capable of providing high-current pulses (for capacitor charging) when the patient requires a shock pulse (e.g., preferably, in excess of 2 A, at voltages above 2 V, for periods of 10 seconds or more). The battery 276 also desirably has a predictable discharge characteristic so that elective replacement time can be detected.

**[0060]** The stimulation device 100 can further include magnet detection circuitry (not shown), coupled to the microcontroller 220, to detect when a magnet is placed over the stimulation device 100. A magnet may be used by a clinician to perform various test functions of the stimulation device 100 and/or to signal the microcontroller 220 that the external programmer 254 is in place to receive or transmit data to the microcontroller 220 through the telemetry circuits 264.

**[0061]** The stimulation device 100 further includes an impedance measuring circuit 278 that is enabled by the microcontroller 220 via a control signal 280. The known uses for an impedance measuring circuit 278 include, but are not limited to, lead impedance surveillance during the acute and chronic phases for proper lead positioning or dislodgement; detecting operable electrodes and automatically switching to an operable pair if dislodgement occurs; measuring respiration or minute ventilation; measuring thoracic impedance for determining shock thresholds; detecting when the device has been implanted; measuring stroke volume; and detecting the opening of heart valves, etc. The impedance measuring circuit 278 is advantageously coupled to the switch 226 so that any desired electrode may be used.

**[0062]** In the case where the stimulation device 100 is intended to operate as an implantable cardioverter/defibrillator (ICD) device, it detects the occurrence of an arrhythmia, and automatically applies an appropriate therapy to the heart aimed at terminating the detected arrhythmia. To this end, the microcontroller 220 further controls a shocking circuit 282 by way of a control signal 284. The shocking circuit 282 generates shocking pulses of low (e.g., up to 0.5 J), moderate (e.g., 0.5 J to 10 J), or high energy (e.g., 11 J to 40 J), as controlled by the microcontroller 220. Such shocking pulses are applied to the patient's heart 102 through at least two shocking electrodes, and as shown in this embodiment, selected from the left atrial coil electrode 126, the RV coil electrode 132, and/or the SVC coil electrode 134. As noted above, the housing 200 may act as an active electrode in combination with the RV electrode 132, or as part of a split electrical vector using the SVC coil electrode 134 or the left atrial coil electrode 126 (i.e., using the RV electrode as a common electrode).

**[0063]** Cardioversion level shocks are generally considered to be of low to moderate energy level (so as to minimize pain felt by the patient), and/or synchronized with an R-wave and/or pertaining to the treatment of tachycardia. Defibrillation shocks are generally of moderate to high energy level (e.g., corresponding to thresholds in the range of approximately 5 J to 40 J), delivered asynchronously (since R-waves may be too disorganized), and pertaining exclusively to the treatment of fibrillation. Accordingly, the microcontroller 220 is capable of controlling the synchronous or asynchronous delivery of the shocking pulses.

#### Physiological Heart Conditions Germane to Therapy

**[0064]** A brief overview of various physiological heart conditions follows wherein various deleterious conditions may benefit from techniques that aim to maintain or increase cardiac output and/or achieve a desirable autonomic balance. Some of the conditions involve activation and/or suppression of autonomic pathways. For example, some conditions are associated with an increased sympathetic tone (e.g., hypersympathetic patients) while others are associated with a decreased parasympathetic tone (e.g., vagally depressed patients). As described further below, various exemplary methods aim to maintain or increase cardiac output in hypersympathetic, vagally depressed and/or congestive heart failure (CHF) patients. In general, such methods call for an increase in parasympathetic tone. In particular, various exemplary methods can have an effect similar to that achieved by administration of an angiotensin-converting enzyme (ACE) inhibitor, which is commonly administered to CHF patients. A brief discussion of CHF and other conditions associated with workload issues follows.

### Congestive Heart Failure (CHF)

**[0065]** Congestive heart failure (CHF) is a condition that is often associated with a weakened heart that cannot pump enough blood to body organs. The amount of blood pumped often corresponds to a workload, which is often a measure of resistance to blood flow. An increase in workload may cause and/or worsen heart failure. Heart failure may affect either the right side, left side, or both sides of the heart. As pumping action is lost, blood may back up into other areas of the body, including the liver, gastrointestinal tract, and extremities (e.g., right-sided heart failure), or the lungs (e.g., left-sided heart failure). Structural or functional causes of heart failure include high blood pressure (hypertension), valvular heart disease, congenital heart diseases, cardiomyopathy, heart tumor, and other heart diseases. Precipitating factors include infections with high fever or complicated infections, use of negative inotropic drugs (such as beta-blockers and calcium channel blocker), anemia, irregular heartbeats (arrhythmias), hyperthyroidism, and kidney disease.

**[0066]** The New York Heart Association (NYHA) has classified heart condition into four classes: Class I - patients with no limitation of activities; they suffer no symptoms from ordinary activities; Class II - patients with slight, mild limitation of activity; they are comfortable with rest or with mild exertion; Class III - patients with marked limitation of activity; they are comfortable only at rest; and Class IV - patients who should be at complete rest, confined to bed or chair; any physical activity brings on discomfort and symptoms occur at rest. Proper treatment of heart failure often relies on assessment of a patient's classification, see, e.g., Shamsham and Mitchell, "Essentials of the diagnosis of heart failure", *Am. Fam. Phys.*, March 1, 2000 (pp. 1319 - 1330). For example, Shamsham and Mitchell present an algorithm for diastolic dysfunction and systolic dysfunction that references the NYHA classes.

### Hypertension, Workload, Cardiac Output and CHF

**[0067]** Hypertension may increase workload, decrease cardiac output and thereby cause or worsen CHF. In fact, hypertension is one of the most common causes of CHF in the United States. Hypertension causes the heart to pump blood against a higher resistance, which requires more force per contraction. The added strain often weakens the myocardium. While a decrease in parasympathetic activity and/or an increase in sympathetic activity may lead to hypertension, diminished parasympathetic response to high blood pressure may also be a mechanism in an increased workload.

### Valvular Heart Disease, Workload, Cardiac Output and CHF

**[0068]** Valvular heart disease may increase workload

and decrease cardiac output by increasing resistance and/or reducing pumping efficiency of the heart, which, in turn, may cause or worsen CHF. Stenotic valves and/or regurgitant valves are often signs of valvular heart disease. Further, endocarditis may damage heart valves. Stenotic valves restrict blood flow and thus increase the heart's workload while regurgitant valves or "leaky" valves allow pumped blood to flow back through a valve. In the latter case, each contraction pumps less blood to the body when compared to a heart with healthy. Endocarditis is an infection that affects heart valves. Damage caused by endocarditis can reduce pumping efficiency.

### Baroreceptor Response, Workload, Cardiac Output and CHF

**[0069]** In healthy individuals, baroreceptors located in the great arteries provide sensory information to second-order barosensitive neurons located in the lower brainstem. Via a number of intermediate neural networks, the second-order neurons affect neurons, which, in turn, affect heart rate and vascular resistance. Thus, baroreceptor activation typically reduces blood pressure and heart rate. However, in a CHF patient, the baroreceptor response is often impaired. A study by Kirchheim et al., "Physiology and pathophysiology of baroreceptor function and neuro-hormonal abnormalities in heart failure", *Basic Res. Cardiol.*, 93(Suppl.1): 1-22 (1998) reported that congestive heart failure is associated with an impairment of the vagally mediated baroreflex bradycardia, and, in general, a reduced vagal tone. Kirchheim et al., further reported that, in CHF patients, angiotensin II may cause a decrease or withdrawal of vagal tone. Overall, Kirchheim et al.'s study of baroreceptor function suggests that the renin-angiotensin-system is linked to autonomic balance, or lack thereof, in congestive heart failure patients.

### ACE Inhibitors, Workload, Cardiac Output and CHF

**[0070]** Angiotensin-converting enzyme (ACE) inhibitors are vasodilator drugs used to decrease pressure by interfering with the conversion of angiotensin I to angiotensin II (a vasoconstrictor), therefore decreasing peripheral vascular resistance. Various studies recommend treatment of CHF using ACE inhibitors, see, e.g., Cohn, "Preventing congestive heart failure", *Am. Fam. Phys.*, April 15, 1998 (pp. 1901 - 1907). A number of potential mechanisms have been suggested to explain the efficacy of ACE inhibitors in preventing congestive heart failure. According to Cohn, the simplest explanation is that ACE inhibitors reduce vascular tone and, by lowering impedance, improve emptying of the left ventricle, which reduces workload. Improved left ventricular systolic performance may also reduce the risk of symptomatic heart failure.

**[0071]** Cohn also reported that another suggested



mechanism involves progressive structural changes that occur in the left ventricular myocardium in patients who develop overt heart failure. In this mechanism, myocardial remodeling is characterized by an enlargement of the chamber and an increase in muscle mass. According to this mechanism, the chamber dilation is associated with a progressive reduction in wall motion, eventually resulting in a globally hypokinetic ventricle. ACE inhibitors have been demonstrated to inhibit remodeling associated with the progressive decline of ejection fraction and overt symptoms of heart failure in both animal and human studies. One disadvantage to ACE inhibitors is that they may result in hyperkalemia (elevated levels of potassium in the blood).

[0072] Other disadvantages of ACE treatment were reported in a study by Frantz, "Beta blockade in patients with congestive heart failure", *Postgraduate Medicine*, 108(8):103 - 118 (2000). Frantz noted that "while ACE inhibitors are now a standard component of CHF therapy... they are not enough". In particular, Frantz suggested the use of beta blockers in patients with left ventricular systolic dysfunction and congestive heart failure (in NYHA classes I, II, and III), in essence, "to treat LV dysfunction, not just the CHF symptoms". However, Frantz also noted that "heart rate of less than 60 beats per minute, symptomatic hypotension, excessive fatigue, and progressive signs and symptoms of CHF may all be indicators that the beta blocker dose needs to be reduced and certainly not escalated". Thus, patient monitoring may help achieve a proper beta blocker dosage.

[0073] While a variety of other treatments exist for patients with decompensated CHF, see, e.g., Loh, "Overview: Old and new controversies in the treatment of advanced congestive heart failure", *J. Card. Fail.*, 7(2 Suppl. 1): 1 - 7 (2001); and Gomberg-Maitland et al., "Treatment of congestive heart failure", *Arch. Intern. Med.*, 161: 342 - 349 (2001), as described below, exemplary autonomic nerve stimulation and/or pacing therapies can beneficially treat CHF and/or related issues by reducing workload, maintaining or increasing cardiac output and/or achieving a desirable autonomic balance.

#### Autonomic Nervous System

[0074] The autonomic nervous system includes sympathetic and parasympathetic pathways. Both pathways include afferent pathways (e.g., from an organ to central neurons) and efferent pathways (e.g., postganglionic neurons from ganglia to an organ) that relate to functioning of the heart. For example, parasympathetic efferent postganglionic neurons, when stimulated, suppress atrial rate and contractile force, atrio-ventricular nodal conduction, and ventricular contractile force, also known as contractility or inotropy. Sympathetic efferent postganglionic neurons, when stimulated, generally increase heart rate and increase contractility. Note that contractility is associated with the term "inotropy", heart

rate is associated with the term "chronotropy" and conduction velocity is associated with the term "dromotropy".

[0075] As already mentioned, the stimulation of parasympathetic nerves can act to decrease heart rate while stimulation of sympathetic nerves can act to increase heart rate. In addition, as noted by Mendelowitz, "Advances in parasympathetic control of heart rate and cardiac function", *News Physiol. Sci.*, 14:155 - 161 (1999), "when both parasympathetic and sympathetic activity are present, parasympathetic activity generally dominates" and "increases in parasympathetic activity to the heart evoke a bradycardia that is more pronounced when there is a high level of sympathetic firing". Mendelowitz also noted that "the release of acetylcholine from parasympathetic neurons might act presynaptically to inhibit the release of norepinephrine from sympathetic nerve terminals".

[0076] Regarding sympathetic stimulation, norepinephrine is released by sympathetic nerves. After its release, norepinephrine acts on the sinoatrial node (SA node) to increase the rate of diastolic depolarization, and thereby increase heart rate, and acts on the atrioventricular node (AV node) to increase the velocity of conduction and diminish the refractory period during which the AV node is unresponsive to stimuli coming from the atrium.

[0077] Contractility (or inotropy) refers to the force or strength of cardiac muscle contractions. Stimulation of sympathetic nerves causes active contractility whereas Frank-Starling mechanism causes passive contractility. Active contractility involves norepinephrine, which increases myocardial calcium permeability (or conductance) and hence actin/myosin crossbridge interactions. Other mechanisms may also accompany the increase in calcium permeability.

[0078] In general, an increase in ventricular contractility causes an increase stroke volume, which, in turn, can increase cardiac output. Cardiac output (CO) depends on heart rate (HR) and stroke volume (SV) (e.g., CO equals HR times SV). Changes in ventricular contractility alter the rate of force and pressure development by the ventricle and therefore change the rate of ejection (i.e., ejection velocity). For example, an increase in contractility shifts the Frank-Starling curve, which causes a reduction in end-systolic volume and an increase in stroke volume. Various exemplary methods described herein aim to increase end diastolic volume and increase passive contractility via the Frank-Starling mechanism. Of course, an increase in parasympathetic tone may also lower resistance to blood flow through the body and hence decrease cardiac workload.

[0079] Various exemplary methods described herein optionally stimulate sympathetic nerves in conjunction with parasympathetic nerves to achieve a desirable autonomic balance - which may depend on respiratory and/or cardiac cycles. For examples, as described below, certain phases of the respiratory cycle may inhibit

parasympathetic response and parasympathetic stimulation may be detrimental to certain phases of a cardiac cycle. In turn, sympathetic stimulation may increase active contractility of the heart. Hence, in one example, parasympathetic stimulation occurs postinspiration only and not during ventricular contraction while sympathetic stimulation occurs during inspiration and during ventricular contraction. In general, appropriate parasympathetic stimulation may act to increase passive contractility and reduce resistance to blood flow through the body while appropriate sympathetic stimulation may increase active contractility. Various exemplary methods aim to reduce heart rate while achieving an desirable cardiac output. Again, an increase in heart rate may worsen a disease state; thus, in some instance, an increase in stroke volume is preferable to an increase in heart rate to achieve a desirable cardiac output.

**[0080]** Changes in inotropic state are particularly important during exercise. Increases in inotropic state helps to maintain stroke volume at high heart rates. Increased heart rate alone decreases stroke volume because of reduced time for diastolic filling (decreased end-diastolic volume). When inotropic state increases at the same time, this decreases end-systolic volume to maintain stroke volume.

**[0081]** Another term used to describe cardiac operation is "cardiac workload", which is sometimes defined as the product of systolic blood pressure and heart rate. In general, an increase in inotropy, chronotropy and/or dromotropy result in an increase in cardiac workload. Further, sympathetic activity is likely to increase cardiac workload whereas parasympathetic activity is likely to decrease cardiac workload. Again, sympathetic tone is often associated with tension and an increase in resistance to blood flow in the body while parasympathetic tone is often associated with relaxation and a decrease in resistance to blood flow in the body.

**[0082]** As already mentioned, the autonomic nervous system includes parasympathetic and sympathetic pathways. Referring to Fig. 3, a simplified diagram of the autonomic nervous system 300 is shown. The system 300 illustrated includes a brain 304, a spinal cord 308, an organ 312, a parasympathetic efferent pathway 318 and a sympathetic efferent pathway 358. The parasympathetic efferent pathway 318 includes a preganglionic cell body 320 located in the brain 304, a preganglionic axon 324, a synaptic cleft 328, a postganglionic cell body 332, a postganglionic axon 336, and a postganglionic synaptic cleft 340 proximate to the organ 312. An exemplary parasympathetic stimulus originates at the brain 304 and ends at the postganglionic synaptic cleft 340 wherein a chemical is emitted to effect cell of the organ 312. A synaptic cleft may also be referred to as a neuroeffector junction. The sympathetic efferent pathway 358 includes a preganglionic cell body 360 located in the spinal cord 308, a preganglionic axon 364, a synaptic cleft 368, a postganglionic cell body 372, a postganglionic axon 376, and a postganglionic synaptic

cleft 380 proximate to the organ 312. An exemplary sympathetic stimulus originates at the spinal cord 308 and ends at the postganglionic synaptic cleft 380 wherein a chemical is emitted to effect cell of the organ 312. In both pathways 318, 358, acetylcholine operates as a neurotransmitter to activate postganglionic neurons, i. e., preganglionic neurons are cholinergic. In parasympathetic pathways (e.g., the parasympathetic pathway 318), postganglionic neurons emit acetylcholine and are therefore cholinergic. However, in many sympathetic pathways (e.g., the sympathetic pathway 358), postganglionic neurons emit norepinephrine and are therefore adrenergic. While Fig. 3 shows a one to one ratio of preganglionic to postganglionic neurons, note that a preganglionic neuron generally links to more than one postganglionic neuron, for example, in a sympathetic pathway, a preganglionic neuron to postganglionic neuron ratio may be approximately 1:32. Autonomic pathways than can affect cardiac operation are described in more detail below.

### Autonomic Pathways

**[0083]** As already mentioned, the autonomic nervous system includes both sympathetic and parasympathetic nerves. In general, the sympathetic nerves and parasympathetic nerves follow pathways, which, as described in more detail below, are at times to some degree intermingled. Intermingling in the vagosympathetic trunks includes, for example, fibers having a sympathetic core surrounded by a parasympathetic vagal skin. Such "vagosympathetic" fibers may arise from one of the vagosympathetic trunks and descend into epicardial and/or endocardial fibers of the heart. Parasympathetic pathways effecting cardiac operation include the vagus nerve, which is a member of a group of nerves commonly referred to as the cranial nerves. Scientifically, the vagus nerve has been designated as the tenth cranial nerve. There are two of these mixed nerves that act to provide both motor and sensory functions. Each vagus nerve contains both somatic and autonomic branches; however, the autonomic function predominates. Vagus nerves are parasympathetic in nature making up 75% of all parasympathetic fibers passing to the thoracic and abdominal regions of the body. As is the case with most nerves, vagi nerves contain both efferent fibers (e.g., to carry an impulse from its origin in the medulla oblongata of the brain to a tissue or an organ), as well as afferent fibers, (e.g., to carry an impulse from a tissue or an organ back to the brain). With vagus nerves, 80% of the fibers are afferent as opposed to efferent. This aids in their active response to the many reflex actions in the body during parasympathetic control. As a whole, the two vagus nerves are very large and work to stimulate a great number of tissues in the body. Vagal stimulation can affect the heart, lungs, esophagus, stomach, small intestine, liver, gall bladder, as well as the upper portions of the ureters.

**[0084]** In general, the right and left vagus nerve pass down the neck as part of right and left vagosympathetic trunks. The right and left vagus also have branches that innervate the heart and lungs. Further down, the left vagus and the right vagus bifurcate into respective left and right ventral and left and right dorsal vagal branches which eventually join. The left and right ventral vagal branches join together to form the ventral vagal trunk on the ventral esophagus while the left and right dorsal vagal branches join together along the dorsal esophagus to form the dorsal vagal trunks. These vagal trunks pass through the esophageal hiatus of the diaphragm and supply the stomach, small intestine, part of the large intestine and major cranial abdominal viscera with parasympathetic innervation. The vagus also includes the right and left recurrent laryngeal nerves, which are somatic, primarily motor subdivisions of the vagus that travel down the neck as part of the right and left vagosympathetic trunks.

**[0085]** Upon stimulation, a vagus nerve releases the hormone acetylcholine at its vagal endings and is, therefore, cholinergic. This is in contrast with adrenergic systems which cause the release of epinephrine and norepinephrine. It is the release of acetylcholine, rather than the passing of nerve impulses that directly initiates a specific response.

**[0086]** Regarding the heart, parasympathetic vagi nerves are distributed to regions of the SA node and the AV node. Release of acetylcholine to these regions typically results in both a decrease in the rate of rhythm of the SA node, as well as a decrease in the cardiac impulse transmission into the ventricles. Consequences of these actions generally include a decrease in heart rate, cardiac output, ventricular contraction, arterial blood pressure, as well as a decrease in overall ventricular pumping.

**[0087]** In general, the right vagus innervates the SA nodal region, the atrial muscle and, to a much lesser degree, the AV nodal region; whereas, the left vagus nerve innervates the SA nodal region and atrial muscle to a lesser degree than it innervates the AV nodal region. Stimulation of the right vagus nerve can predominately slow the SA node rate and thereby reduces heart rate; whereas, stimulation of the left vagus nerve can produce some slowing of the SA node, prolongation of AV conduction and partial or total AV block.

**[0088]** The vagi nerves are also involved in a process known as respiratory sinus arrhythmia (RSA). As stated in Mendelowitz, "Advances in parasympathetic control of heart rate and cardiac function", *News Physiol. Sci.*, 14:155 - 161 (1999), in RSA, "the heart beats more rapidly in inspiration and slows during postinspiration and expiration". Further, Mendelowitz noted that "cardiac vagal neurons recorded in vivo receive inhibitory synaptic input during inspiration, which is then followed by a rapid depolarization caused by excitatory synaptic input during postinspiration".

**[0089]** Referring to Fig. 4, a block diagram of various

components of the autonomic nervous system is shown. While Fig. 4 pertains primarily to sympathetic pathways, as already mentioned, intermingling of sympathetic pathways and parasympathetic pathways typically occurs to some degree at various points. The sympathetic nervous system, which is not part of the central nervous system, includes two parallel chains or trunks, a right trunk 406 and a left trunk 406'. Each trunk includes a series of ganglia which lie just lateral to the spinal cord 404 on each side (left and right). In general, the uppermost region of each trunk (406, 406') has three cervical ganglia, which are continuous with the thoracic trunk. The cervical ganglia are known as the right and left superior cervical ganglia (408, 408'), the right and left middle cervical ganglia (412, 412') and the right and left inferior cervical ganglia (416, 416'), the latter of which are known as a stellate ganglion if they combine with a respective first thoracic ganglion. Stellate ganglia exist in approximately 70% to approximately 80% of the population.

**[0090]** Cardiac sympathetic fibers originate in intermediolateral columns of the upper five or six thoracic segments (see T1 - T6 in Fig. 4) and lower one or two cervical segments (see C5 and C6 in Fig. 4) of the spinal cord 404. Sympathetic fibers enter the paravertebral chain and typically synapse in the cervical ganglia. Cardiac sympathetic ganglia are generally found close to the spinal column (paravertebral ganglia) and may stem from both thoracic and cervical preganglionic fibers. Postganglionic cardiac sympathetic nerves originate from the left and right ganglia and usually approach the base of the heart (e.g., as superior, middle, and inferior cardiac nerves) along the adventitial surface of the great vessels.

**[0091]** Each of the superior cardiac nerves 432, 432' arises by two or more branches from a respective superior cervical ganglion 408, 408', and occasionally receives a filament from the trunk between a first and/or a second cervical ganglia. The right superior cardiac nerve 432, at the root of the neck, passes either in front of or behind the subclavian artery, and along the innominate artery to the back of the arch of the aorta, where it joins the deep part 428, 428' of the epicardial plexus 420. The right superior cardiac nerve 432 connects with other sympathetic branches. About the middle of the neck the right superior cardiac nerve 432 receives filaments from the external laryngeal nerve; lower down, one or two twigs from the vagus; and as it enters the thorax it is joined by a filament from the recurrent nerve. In addition, filaments from the nerve communicate with the thyroid branches from the right middle cervical ganglion 412. The left superior cardiac nerve 432', in the thorax, runs in front of the left common carotid artery and across the left side of the arch of the aorta, to the superficial part 424 of the epicardial plexus 420.

**[0092]** Each of the middle cardiac nerves 436, 436' (or great cardiac nerves), the largest of the three cardiac nerves, arises from a respective middle cervical gangli-

on 412, 412', or from a respective trunk 406, 406' between the middle ganglion 412, 412' and the inferior ganglion 416, 416'. On the right side, the right middle cardiac nerve 436 descends behind the common carotid artery, and at the root of the neck runs either in front of or behind the subclavian artery; it then descends on the trachea, receives a few filaments from the recurrent nerve, and joins the right half of the deep part 428 of the epicardial plexus 420. In the neck, it communicates with the right superior cardiac nerve 432 and recurrent nerve. On the left side, the left middle cardiac nerve 436' enters the chest between the left carotid and subclavian arteries, and joins the left half of the deep part 428' of the epicardial plexus 420.

**[0093]** Each inferior cardiac nerve 440, 440' arises from the respective inferior cervical ganglion 416, 416' or the first thoracic ganglion (or stellate ganglion, e.g., 416, 416'). Both right and left inferior cardiac nerves 440, 440' descend behind the subclavian artery and along the front of the trachea, to join the deep part 428, 428' of the epicardial plexus 420. Each of the inferior cardiac nerves 440, 440' communicates freely behind the subclavian artery with the recurrent nerve and the respective middle cardiac nerve 436, 436'.

**[0094]** As already mentioned with reference to Fig. 4, at the base of the heart, the sympathetic fibers form an epicardial plexus 420 that distributes the fibers to the various regions of the heart. The epicardial plexus 420 has a superficial part 424 and a deep part (shown as a right deep part 428 and a left deep part 428' in Fig. 4), see, e.g., Gray's anatomy: the anatomical basis of medicine and surgery, 38th ed. (1995). The deep part 428, 428' lies upon the tracheal bifurcation (at the back of the aorta and in front of the tracheal bifurcation) and consists of cardiac branches from all cervical sympathetic ganglia of both right and left sides except the superior left 408', together with superior and inferior cervical and thoracic cardiac branches of the right vagus nerve (parasympathetic) and superior cervical and thoracic branches of the left vagus nerve (parasympathetic).

**[0095]** Referring to Fig. 5, an approximate anatomical diagram of afferent vagal parasympathetic pathways 520, 520' is shown. Vagal afferent pathways include baroreceptors and/or chemoreceptors from the aortic arch 504, carotid arteries 508, 508' and the heart 502. With respect to the heart 502, vagus afferent pathways are known to have receptors associated with atria, ventricles, pulmonary arteries and coronary arteries. Also shown in Fig. 5 are the glossopharyngeal nerves 530, 530' and sinus branches thereof 532, 532'. In general, such afferent pathways lead to the nucleus tractus solitarius in the brainstem. In addition, stimulation of such afferent pathways typically leads to a depressor response. However, a controversial and seemingly undocumented (in humans) reflex known as the "Bainbridge reflex" can increase heart rate due to an increase of the right atrial pressure. In general, cardiac receptors that lead to a neural response are classified as "A" or "B"

receptors. B receptors are the predominant stretch receptors and are stimulated by passive stretch of the atria usually during later diastole. B receptors, when stimulated, cause a response similar to baroreceptors, e.g., inhibition of sympathetic nerves and/or excitation of parasympathetic nerves.

**[0096]** Another group of receptors known as left atrial volume receptors respond to increases in transmural pressure: e.g. from increased left atrial volume. Impulses transmitted to the osmoregulatory centers of the hypothalamus result in reduced ADH (antidiuretic hormone, vasopressin) secretion thereby increasing body water loss. Reflex hypotension and bradycardia sometimes follow left atrial distention. With hemorrhage and decreases in left atrial pressure, ADH secretion is increased to induce water retention. Receptors can also cause hormone secretion. For example, mammalian atria have secretory granules containing a small peptide, atrial natriuretic peptide (ANP). ANP is secreted on stretch of the atria. This potent, short lived peptide induces renal secretion of sodium and increase diuresis thus serving to decrease volume. ANP appears to act to decrease CO by decreasing systemic resistance and by increase capillary filtration.

**[0097]** Ventricular, mostly left ventricle, responses include the Bezold-Jarish Reflex, which results from ventricular wall distention stimulating ventricular mechanoreceptors. Such receptors appear to be active only with extreme conditions to protect the ventricle from volume overload (elicit hypotension and bradycardia). The response is a reflex vagal slowing of the heart and simultaneous inhibition of sympathoadrenal activity. The reflex protects against cardiac overstrain, pulmonary edema, and hypovolemia whenever cardiac distention is excessive (e.g., in some CHF patients). The reflex, transmitted by afferent vagal fibers, is thought to exert its sympathetic block via release of endogenous opioids likely acting on the delta-type opioid receptors in the brain.

#### Epicardial Autonomic Pathways

**[0098]** Pauza et al., "Morphology, distribution, and variability of the epicardiac neural ganglionated subplexuses in the human heart", The Anatomical Record 259(4): 353 - 382 (2000), reported that the epicardial plexus forms seven subplexuses: (I) left coronary, (II) right coronary, (III) ventral right atrial, (IV) ventral left atrial, (V) left dorsal, (VI) middle dorsal, and (VII) dorsal right atrial. Pauza et al., state that, in general, the human right atrium is innervated by two subplexuses (III, VII), the left atrium by three subplexuses (IV, V, VI), the right ventricle by one subplexus (II), and the left ventricle by three subplexuses (I, V, VI). Pauza et al., also note that diagrams from Mizeres, "The cardiac plexus in man", Am. J. Anat. 112:141 - 151 (1963), suggest that "left epicardiac subplexuses may be considered as being formed by nerves derived from the left side of the deep

extrinsic cardiac plexus, whereas ventral and dorsal right atrial subplexuses should be considered as being supplied by preganglionated nerves extending from the right vagus nerve and right sympathetic trunk, as their branches course in the adventitia of the right pulmonary artery and superior vena cava". Further, Pauza et al., also state that the left coronary (I), right coronary (II), ventral left atrial (IV) and middle dorsal (VI) subplexuses "may be considered as being formed by the deep extrinsic plexus that receives equally from both vagi and sympathetic trunks". Note that in the Pauza et al., reference, the terms "epicardiac preganglionated nerves" and "epicardiac postganglionated nerves" are differentiated from the meanings of "axons of the preganglionic and postganglionic neurons" that are valid in the nomenclature of the autonomic nervous system, for example, as referred to above with reference to Fig. 3 and Fig. 4. Thus, the term "postganglionic neurons" includes epicardiac/epicardial preganglionic neurons as well as epicardiac/epicardial postganglionic neurons.

#### Neuroeffectors

**[0099]** Upon stimulation, end terminals (or terminal knobs) of the postganglionic sympathetic nerves (e.g., epicardial postganglionic sympathetic nerves) release norepinephrine, which acts upon the myocardium. Following stimulation and release, norepinephrine remains active for several seconds; norepinephrine may then be reabsorbed by the terminal, diffuse out of the area, or be inactivated by enzymes. The adrenal medulla also secretes norepinephrine (e.g., 75 percent epinephrine and 25 percent norepinephrine) and produces a peripheral effect that typically lasts much longer than that produced by stimulation of the sympathetic postganglionic terminal knobs. While circulating norepinephrine can increase contractility, the effect on normally innervated hearts is relatively minor with respect to norepinephrine released by end terminals. Heart rate, although initially stimulated by norepinephrine, usually decreases over time due to activation of baroreceptors and vagal-mediated (parasympathetic) slowing of the heart rate.

**[0100]** Cardiac tissue membrane receptors, such as alpha receptors and beta receptors, receive chemicals emitted by postganglionic nerves. Alpha receptors are the most common type of sympathetic receptor and they respond strongly to norepinephrine and weakly to epinephrine. Beta receptors are also adrenergic and include beta-1, beta-2 and beta-3 receptors. Cardiac sympathetic receptors are mostly the beta-1 subtype. Beta-1 receptors, which respond approximately equally to norepinephrine and epinephrine, generally act on the myocardium to increase heart rate, contractility, and/or conduction velocity. In contrast, parasympathetic cholinergic muscarinic receptors act on the sinoatrial (SA) node to decrease heart rate and act on the atrioventricular (AV) node to decrease conduction velocity. Adrenergic antagonists (indirect action) include beta-

blockers such as propranolol and alpha-blockers such as phentolamine that inhibit receptors. Cholinergic antagonists (indirect action) include alpha-blockers such as atropine.

#### Exemplary Detection of Factors Related to Workload and/or Cardiac Output

**[0101]** Various exemplary methods presented below rely on detection of a need to decrease workload and/or detection of a need to maintain or increase cardiac output (e.g., by increasing passive contractility and/or active contractility and not necessarily by increasing heart rate). With respect to workload, such a need may be determined using factors related to workload or afterload. Afterload typically increases when aortic pressure and systemic vascular resistance are increased, for example, by aortic valve stenosis, ventricular dilation (e.g., hypertrophy), etc. When afterload increases, there is an increase in end-systolic volume and a decrease in stroke volume. Thus, if heart rate does not increase, cardiac output will drop. An increase in afterload generally decreases velocity of fiber shortening. Because the period of time available for ejection is finite (~150-200 msec), a decrease in fiber shortening velocity reduces the rate of volume ejection so that more blood is left within the ventricle at the end of systole (increase end-systolic volume).

**[0102]** An exemplary implantable device optionally includes a blood pressure sensor that can sense blood pressure; accordingly, if sensed blood pressure is above a threshold value, then a need for decreased workload may exist. In addition, blood pressure may signal a need to maintain or increase cardiac output by increasing stroke volume and optionally decreasing heart rate. In this example, the sensor may sense afterload pressure, which is the initial pressure of systole. The afterload pressure or resistance is typically a measure of systemic vascular resistance and generally represents the sum of all forces which oppose ventricular muscle shortening during systole. Of course, other factors related hemodynamics may be used (e.g., flow rate, etc.).

**[0103]** As described, while an increase in workload may indicate a need to adjust cardiac output, a decrease in cardiac output may indicate a need to decrease workload. If myocardial function is severely depressed, cardiac output may become crucially afterload-dependent. In such circumstances, cardiac output may be an indicator of a need to decrease workload. Further, an increase in cardiac output may indicate that workload has decreased.

**[0104]** A need to decrease workload and/or to maintain or increase cardiac output may be based on cardiac velocity. For example, under conditions of constant preload, the initial velocity of shortening of isolated papillary muscle falls progressively as afterload is increased, particularly if afterload becomes excessive.

**[0105]** A need to decrease workload and/or to main-

tain or increase cardiac output may also be based on cardiac electrical activity. For example, variance in R-to-R intervals may indicate when a decrease in workload would be beneficial. Variance in R-to-R intervals may reflect heart rate turbulence. Again, an increase in heart rate may be considered a normal physiological response to an increase in workload or a decrease in cardiac output.

#### Electrical and/or Magnetic Stimulation of Autonomic Nerves

**[0106]** Electrical stimulation of autonomic nerves has been reported in the literature, see, e.g., Murakami et al., "Effects of cardiac sympathetic nerve stimulation on the left ventricular end-systolic pressure-volume relationship and plasma norepinephrine dynamics in dogs", *Jpn. Circ. J.* 61(10): 864-71 (1997); and Du et al., "Response to cardiac sympathetic activation in transgenic mice overexpressing beta 2-adrenergic receptor". *Am. J-Physiol.* Aug; 271(2 Pt 2): H630-6 (1996). Magnetic stimulation of nerves has also been reported, for example, where a nerve is exposed to a time-varying magnetic field, which may induce electrical currents in the nerve.

**[0107]** According to various exemplary methods and/or devices described herein, a series of pulses, or a pulse train, is typically delivered by an implantable stimulation device to stimulate an autonomic nerve. The pulse train optionally includes pulse parameters or pulse train parameters, such as, but not limited to, frequency, pulse duration (or pulse width), number of pulses, and/or amplitude. These parameters may have broad ranges and vary over time within any given pulse train. In general, a power level for individual pulses and/or pulse trains is determined based on these parameters and/or other parameters. Exemplary ranges for pulse frequency include frequencies ranging from approximately 0.1 to approximately 50 Hz, and, in particular, frequencies ranging from approximately 1 Hz to approximately 20 Hz. Of course, higher frequencies higher than 50 Hz may also be suitable. Exemplary ranges for pulse duration, or pulse width for an individual pulse (generally within a pulse train), include pulse widths ranging from approximately 0.01 milliseconds to approximately 5 milliseconds and, in particular, pulse widths ranging from approximately 0.1 milliseconds to approximately 2 milliseconds. Exemplary pulse amplitudes are typically given in terms of current or voltage; however, a pulse or a pulse trains may also be specified by power, charge and/or energy. For example, in terms of current, exemplary ranges for pulse amplitude include amplitudes ranging from approximately 0.02 mA to approximately 20 mA, in particular, ranging from 0.1 mA to approximately 5 mA. Exemplary ranges for pulse amplitude in terms of voltage include voltages ranging from approximately 1 V to approximately 50 V, in particular, ranging from approximately 1 V to approximately 15 V.

**[0108]** For pulses delivered by implantable stimulation devices having a fixed or otherwise limited power supply, i.e., a power supply having power limitations, average power of a pulse or a pulse train is usually limited acutely by the power capability of the power supply (e.g., battery; fuel cell, nuclear generator, etc.) and chronically by the capacity of the power supply and desired longevity of the device's usefulness. Average power of a pulse is generally given as peak power averaged over one cycle. For example, given a voltage of 10 V, a resistance of 1000 ohms, a pulse frequency of 20 Hz and a pulse width of 1 ms, the peak power is given as voltage squared divided by resistance, which is 0.1 W, and the average power is 20 Hz multiplied by 1 ms multiplied by 0.1 W, which is 0.002 W or 2 mW. The term "power", as used herein, includes, but is not limited to, peak power and average power.

**[0109]** Current drain is another factor often considered when determining power limitations of a power supply. Current drain is generally defined as the average amount of current drawn from a power supply in an implantable pulse generator in one hour. Current drain depends on many factors, including how frequently the device delivers pulses and at what parameters, the circuitry and/or the type of stimulation lead. Current drain is commonly expressed in millionths of an ampere or microamperes. A power drain based on current drain may be determined by the product of current drain and voltage. Such a power is optionally useful in determining a maximum power level for an autonomic stimulation pulse or pulses.

**[0110]** In general, a maximum power level or maximum power demand for an implantable device may be determined, in part, by the product of the voltage times the current capability of the battery (or other power supply) less circuit inefficiencies. Of course, desired power supply life (e.g., battery life) and/or other factors may be considered. For example, some implantable stimulation devices have a continuous power drain for one function (e.g., to drive a microchip, microprocessor or timing circuitry) and an intermittent function (e.g., such as pacing, measuring, signaling, etc.) which has intermittent power utilization. Consideration of such factors may be necessary in determining a tolerable and/or maximum power level and, in particular, in determining pulse parameters for autonomic nerve stimulation.

#### Vessels and Stimulation of Autonomic Pathways

**[0111]** According to various exemplary methods and stimulation devices described herein, and equivalents thereof, stimulation of parasympathetic nerves allows for influence of cardiac activity. For example, various exemplary methods and corresponding stimulation devices rely on placement of one or more electrodes in a vessel, e.g., an epicardial vein or an epicardial venous structure. Suitable epicardial veins or venous structures include the coronary sinus and veins that drain into the

coronary sinus, either directly or indirectly. For example, the great cardiac vein passes along the interventricular sulcus, with the anterior interventricular coronary artery, and empties anteriorly into the coronary sinus; and the middle cardiac vein travels with the posterior (right) interventricular coronary artery and empties into the coronary sinus posteriorly. Other suitable veins include those that drain into the right atrium or right auricle. For example, the anterior cardiac vein passes through the wall of the right atrium and empties into the right atrium.

[0112] Other exemplary methods and/or devices rely on placement of one or more electrodes in a non-epicardial vein. Such exemplary methods and/or devices are optionally suitable for stimulation of parasympathetic nerves at locations, for example, generally along a parasympathetic pathway between the heart and brain. Further, other exemplary methods and/or devices rely on placing one or more electrodes through the wall of a vein and proximate to a parasympathetic nerve.

[0113] Referring to Fig. 6, a ventral diagram of a human heart 602 is shown. Various anatomical features of the heart 602 are also shown and include an opening to the superior vena cava 606, an opening to the aorta 610, an opening to the pulmonary trunk 614, an opening to the right superior pulmonary vein 618, an opening to the left inferior pulmonary vein 622, and an opening to the left superior pulmonary vein 626. Fig. 6 also shows some of the epicardial arteries (thick dashed lines) and veins (thick solid lines). Under normal conditions, epicardial arteries carry oxygenated blood to the myocardium, primarily myocardium of the ventricles while epicardial veins carry blood deoxygenated by the myocardium to the right atrium of heart 602. Pressure in the veins is generally, on average, much less than pressure in the arteries.

[0114] Two major epicardial arterial networks are shown in Fig. 6 and associated with the left coronary artery 630 and the right coronary artery 634. The left coronary artery 630 stems from the aorta near the opening to the aorta 610 and travels along the base of the left ventricle where it branches. One branch of the left coronary artery travels on the epicardial surface of the left ventricle toward the apex of the heart 602 (known as the left anterior descending artery) while another branch travels on the epicardial surface of the left ventricle toward the dorsal side of the heart 602 (known as the circumflex branch of the left coronary artery). The right coronary artery 634 stems from the aorta near the opening to the aorta 610 and travels along the base of the right ventricle where it branches. Various branches of the right coronary artery 634 travel on the epicardial surface of the right ventricle while at least one branch travels on the epicardial surface of the right ventricle toward the dorsal side of the heart 602.

[0115] Three major epicardial venous networks are shown in Fig. 6, which are associated with the great cardiac vein 638, the anterior cardiac vein 642, and the small cardiac vein 646. The great cardiac vein 638 re-

ceives blood from a network that spreads across the ventral side of the epicardial surface of the left ventricle and major branches of the network extend toward the apex of the heart 602. As already mentioned, the great cardiac vein 638 travels on the epicardial surface near the base of the left ventricle to the dorsal side of the heart 602 where it joins the coronary sinus vein. The anterior cardiac vein 642 receives blood from a network that spreads across the ventral and dorsal sides of the epicardial surface of the right ventricle and major branches of the network extend toward the apex of the heart 602. As already mentioned, the anterior cardiac vein empties into the right atrium of the heart 602. The small cardiac vein 646 travels from the ventral epicardial surface to the dorsal epicardial surface where it empties into the coronary sinus.

[0116] Fig. 6 also shows the seven subplexuses as identified by Pauza et al. Preganglionic nerves enter the left coronary subplexus (I) and the right coronary subplexus (II) approximately between the opening to the aorta 610 and the opening to the pulmonary trunk 614. Preganglionic nerves enter the ventral right atrial subplexus (III) at the superior interatrial sulcus and non-regularly on the ventral surface of the root of the superior vena cava while preganglionated nerves enter the ventral left atrial subplexus (IV) approximately between the superior interatrial sulcus and left atrial nerve fold. Preganglionated nerves enter the left dorsal subplexus (V) approximately at the left atrial nerve fold and preganglionated nerves enter the middle dorsal subplexus (VI) approximately between the right and left superior pulmonary veins (see, e.g., 618, 626) and, non-regularly, between the right pulmonary veins and the inferior vena cava. Preganglionated nerves enter the dorsal right atrial subplexus (VII) approximately between the superior vena cava and the right superior pulmonary vein (see, e.g., 606, 618). As already mentioned, postganglionated nerves, and some preganglionated nerves, spread out from the subplexuses (I - VII) across the epicardial surface of the heart 602. The spreading of such nerves is shown by the thick solid arrows in Fig. 6 and Fig. 6, the latter of which shows a dorsal diagram of the heart 602.

[0117] Referring to Fig. 7, a dorsal diagram of the human heart 602 is shown. Various anatomical features of the heart 602 are also shown and include an opening to the superior vena cava 606, an opening to the inferior vena cava 624, an opening to the right inferior pulmonary vein 628, and an opening to the left inferior pulmonary vein 622. Fig. 7 also shows some of the epicardial arteries (thick dashed lines) and veins (thick solid lines). The arterial and venous networks shown on the dorsal epicardial surface of the heart 602 include extensions of networks from the ventral epicardial surface. For example, the dorsal epicardial surface includes networks stemming the right coronary artery 634 and the left coronary artery 630. In particular, the circumflex branch of the left coronary artery 630 is shown along with various



extensions of the right coronary artery 634 one of which approaches the end of the circumflex branch. Venous epicardial structures shown in Fig. 6 include the coronary sinus 662, the great cardiac vein 638, the small cardiac vein 646, the oblique vein of the left atrium 652, the left marginal vein 650, the posterior vein of the left ventricle 654, and the middle cardiac vein 658. The aforementioned veins (638, 646, 650, 652, 654, 658) empty into the coronary sinus 662.

[0118] Fig. 7 also shows, via thick solid arrows, neural extensions of five of the subplexuses as identified by Pauza et al. Neural extensions of the left coronary subplexus (I) descend toward the apex of the heart 602 at and/or near the left marginal vein 650 and the posterior vein of the left ventricle 654. Neural extensions of the right coronary subplexus (II) traverse the heart 602 at and/or near the right coronary sulcus. Neural extensions of the left dorsal subplexus (V) descend toward the apex of the heart 602 at and/or near the posterior vein of the left ventricle 654 while neural extensions of the middle dorsal subplexus (VI) descend towards the apex of the heart 602 at and/or near the middle cardiac vein 658 and the small cardiac vein 646. Neural extensions of the dorsal right atrial subplexus (VII) extend around the right atrium at and/or near the superior vena cava (see, e.g., 606) and the inferior vena cava (see, e.g., 624).

[0119] As shown in Figs. 6 and 7, various epicardial veins or venous structures travel at and/or near epicardial subplexuses and/or epicardial extensions of epicardial subplexuses. According to various exemplary methods and/or stimulation devices described herein, at least one electrode is placed in the lumen of an epicardial vein or venous structure and/or through the wall of an epicardial vein or venous structure. Further, upon passing current through the at least one electrode, neural stimulation occurs, which preferably causes release of a neuroeffector, such as, but not limited to, acetylcholine.

#### Stimulation of Non-epicardial Parasympathetic Pathways

[0120] A study by Sokolavas et al., "Surgical parasympathetic AV node denervation in a canine model: anatomical and electrophysiological studies", HeartWeb, 2(1), No. 96110010 (1996), concluded that "only the parasympathetic nerve fibers reach the AV node over the left dorsal and the middle septal nerve subplexuses". In humans, these two subplexuses correspond to the left dorsal (V) and the middle dorsal (VI) subplexuses. Sokolavas et al., reached their conclusion, in part, through stimulation of the left vagosympathetic trunk. In particular, Sokolavas et al., placed a silver electrode on the left vagosympathetic trunk and delivered rectangular stimulation pulses having a frequency of 30 Hz, a duration of 1 ms and a potential of 0.5 V to 2 V. Such pulses were able to eventually produce a first degree AV block.

#### Various Exemplary Methods and/or Devices

[0121] Referring to Fig. 8, an exemplary method 800 involves positioning one or more electrodes, for example, proximate to the left vagosympathetic trunk and/or a branch thereof and delivering a stimulation pulse to the one or more electrodes to thereby stimulate a parasympathetic nerve. More specifically, in a detection block 804, a need for increased cardiac output is detected. Such a need may be detected based on information from a sensor, from a patient, from a physician, etc. For example, a patient may experience weight gain due to excessive fluid retention, which is a condition that may indicate a need for increased cardiac output. In a stimulation block 808, a stimulation pulse or pulses stimulate a parasympathetic nerve in response to the detected need for increased cardiac output. A decision block 812 follows that determines if the parasympathetic stimulation has caused a sufficient increase in cardiac output, for example, via an increased end diastolic volume and a resulting increase in passive contractility (e.g., Frank-Starling mechanism). If the decision block 812 determines that there is no increase or an insufficient increase, then the method 800 continues at an adjustment block 820. The adjustment block 820 adjusts one or more parameters associated with the stimulation of the stimulation block 808. In this instance, at the stimulation block 808, stimulation either continues or repeats using the one or more adjusted parameters.

[0122] In the case that the decision block 812 determines that there is a sufficient increase in cardiac output, the method 800 may continue at another decision block 816, which determines if ventricular pacing is available. If ventricular pacing is available, then the exemplary method 800 may initiate ventricular pacing at a ventricular pacing block 824 wherein the pacing occurs at an appropriate reduced rate. Again, a goal of various exemplary methods or devices described herein is to reduce heart rate while maintaining sufficient cardiac output. In diseased hearts, low stroke volume is often compensated for by an elevation in heart rate in an effort to achieve a suitable cardiac output. Such a course typically worsens the disease state; whereas, the exemplary method 800 aims to maintain or increase cardiac output by increasing stroke volume and not heart rate.

[0123] An exemplary device suitable for implementing the exemplary method 800 may include a lead having one or more electrodes positionable proximate to the left vagosympathetic trunk and/or a branch thereof and hardware and/or software configured to deliver a stimulation pulse to the one or more electrodes. The exemplary method and/or device optionally deliver a stimulation pulse postinspiration and/or in synchrony with one or more cardiac events. In this example, such a device and method may even result in some degree of AV block if ventricular pacing is available. Of course, in instances where ventricular pacing is not available, induction of any significant AV block should be avoided.



**[0124]** Fig. 9 shows an exemplary method 900 wherein AV conduction is taken into consideration. In a detection block 904, a need for increased cardiac output is detected. Such a need may be detected based on information from a sensor, from a patient, from a physician, etc. In a stimulation block 908, a stimulation pulse or pulses stimulate a parasympathetic nerve in response to the detected need for increased cardiac output. A decision block 912 follows that determines if there is adequate AV conduction, for example, that AV nodal filtering of atrial activation wavefronts does not exceed a set limit (e.g., 2:1, etc.). If the decision block 912 determines that AV conduction is inadequate, then an adjustment block 920 adjusts one or more parasympathetic stimulation parameters in a manner that aims to restore AV conduction to an adequate state. In Fig. 9, a minus sign indicates negative feedback. If the decision block 912 determines that there is adequate AV conduction, then the method 900 continues in another decision block 916 that determines whether the stimulation resulted in a sufficient increase in cardiac output.

**[0125]** If the decision block 916 determines that no increase or an insufficient increase in cardiac output results, then the method 900 continues in the adjustment block 920; however, in this instance, there is positive feedback, as indicated by the plus sign. Of course, a situation may exist wherein the increase is more than sufficient or desired and negative feedback is sent to the adjustment block. In general, parasympathetic stimulation power or duty cycle may be ramped up in a manner to avoid such an overshoot. If the decision block 916 determines that the increase was sufficient, then the method 900 may return to the detection block 904, which may monitor cardiac output to see if any subsequent increases are needed. As in the exemplary method 800, the parasympathetic stimulation aims to cause a sufficient increase in cardiac output, for example, via an increased end diastolic volume and a resulting increase in passive contractility (e.g., Frank-Starling mechanism).

**[0126]** Fig. 10 shows another exemplary method 1000 which optionally implements ventricular pacing to overcome inadequate AV conduction. In a detection block 1004, an increase in sympathetic tone, activity, etc. is detected. Such detection may be based on information from a sensor, from a patient, from a physician, etc. In a stimulation block 1008, a stimulation pulse or pulses stimulate a parasympathetic nerve in response to the detected increase in sympathetic tone (e.g., typically an increase that is not offset by an increase in parasympathetic tone). A decision block 1012 follows that determines if there is adequate AV conduction, for example, that AV nodal filtering of atrial activation wavefronts does not exceed a set limit (e.g., 2:1, etc.). If the decision block 1012 determines that AV conduction is inadequate, then an implementation block 1016 implements ventricular pacing. Of course, an exemplary method may include options of adjusting one or more

parasympathetic stimulation parameters and/or implementing ventricular pacing, where available.

**[0127]** As shown in Fig. 10, the exemplary method 1000 implements ventricular pacing to overcome inadequate AV conduction. If the decision block 1012 determines that AV conduction is adequate, then the method 1000 continues in another decision block 1020, which determines if autonomic balance is sufficient. If autonomic balance is not sufficient, for example, too little or too much parasympathetic tone, then the method 1000 continues in an adjustment block 1024 that adjusts one or more stimulation parameters in an effort to achieve a sufficient autonomic balance. The method 1000 may continue in the stimulation block 1008 wherein parasympathetic stimulation continues or repeats using the one or more adjusted parameters. Of course where too much parasympathetic tone exists, a wait block, a sympathetic stimulation block or another block may occur. In the exemplary method 1000, the decision block 1020 typically provides positive feedback to the adjustment block 1024, especially wherein parasympathetic stimulation power and/or duty cycle are ramped up over time.

**[0128]** Yet another exemplary method involves stimulation of afferent parasympathetic nerves. A study by Kawada et al., "Vagosympathetic interactions in ischemia-induced myocardial norepinephrine and acetylcholine release", *Am. J. Physiol. Heart Circ. Physiol.*, 280:H216 - H221 (2001), reported that, in animals subject to occlusion of their left anterior descending coronary artery, a resulting increase in sympathetic activity was diminished by vagal afferent activity. In particular, vagal afferent activity reduced ischemia-induced myocardial norepinephrine release.

**[0129]** An exemplary device for implementing such an exemplary method may include a lead having one or more electrodes positionable proximate to a vagal afferent nerve and hardware and/or software configured to deliver a stimulation pulse to the one or more electrodes. The exemplary method and/or device optionally deliver a stimulation pulse postinspiration and/or in synchrony with one or more events in a cardiac cycle. A desirable effect of such an exemplary method and/or device is to reduce myocardial norepinephrine release and/or concentrations, which may, in turn, allow parasympathetic effects to increase end diastolic volume and passive contractility.

**[0130]** An exemplary method optionally adjusts parasympathetic stimulation power (e.g., amplitude, frequency, duty, etc.) as a function of heart rate. For example, if an increase in heart rate occurs, an increase in parasympathetic stimulation power duty may occur in an effort to increase stroke volume, decrease workload, and/or maintain or increase cardiac output. In another example, an increase in cardiac output or stroke volume (e.g., end diastolic volume) may cause a decrease in stimulation power.

**[0131]** In another exemplary method, parasympathetic stimulation halts after a period of time. For example,

a physician may wish to see the effects of parasympathetic stimulation on a patient. Thus, such an exemplary method may halt parasympathetic stimulation after one month. The physician may then examine the course of the patient's condition post-parasympathetic stimulation to determine if the condition worsens or the rate at which it returns to a pre-parasympathetic stimulation period state. Of course, an exemplary device may optionally include an algorithm for such diagnostics. Further, such an algorithm may include comparing current results to past results. Yet further, such an algorithm may reinitiate parasympathetic stimulation based on the comparing or some other basis (e.g., time, measurement, etc.).

#### Stimulation of Epicardial Parasympathetic Pathways

**[0132]** Referring again to Figs. 6 and 7, various epicardial vessels are shown along with various subplexuses. Fig. 11 is an approximate anatomical diagram of a ventral view of a heart that corresponds to the diagram of Fig. 6. In Fig. 11, exemplary leads having exemplary electrodes are also shown in exemplary epicardial locations. For example, Fig. 11 shows the exemplary stimulation device 100 of Fig. 1 having four leads 104, 106, 108, 110. The leads 104, 106, 108, 110 optionally include branches or bifurcations. In this example, any of the leads may carry electrodes suitable for stimulation of autonomic nerves. As shown in Fig. 11, one exemplary lead 110 has an electrode portion having three electrodes 144, 144', 144". The electrode portion of the lead 110 passes through the wall of the anterior cardiac vein 642 and extends along nerves emanating from the VRA (III) subplexus. Having an electrode portion of a lead positioned as such, activation of at least one of the electrodes 144, 144', 144" optionally stimulate nerves to affect operation of the SA node.

**[0133]** In a similar manner, another exemplary lead 110' has an electrode portion having three electrodes 145, 145', 145". The electrode portion of the lead 110' passes through the wall of the great cardiac vein 638 and extends along nerves emanating from the LD (V) subplexus. Having an electrode portion of a lead positioned as such, activation of at least one of the electrodes 145, 145', 145" optionally stimulate nerves to affect operation of the AV node. Yet another exemplary lead 110" has an electrode portion having three electrodes 146, 146', 146". The electrode portion of the lead 110" passes through the wall of the superior vena cava (see, e.g., opening of superior vena cava labeled 606) and extends to the VRA (III) subplexus and/or DRA (VII) subplexus. Having an electrode portion of a lead positioned as such, activation of at least one of the electrodes 146, 146', 146" optionally stimulate nerves to affect operation of the SA node. Of course, the locations and functions of the three leads 110, 110', 110" are only exemplary as a variety of other arrangements are possible. In general, leads may extend to pre-ganglionated field regions, ganglionated field regions and/or post-

ganglionated field regions. More specifically, leads optionally extend to pre-ganglionated field regions, ganglionated field regions and/or post-ganglionated field regions associated with at least one of the seven subplexuses identified in the Pauza et al. reference. While the leads shown in Fig. 11 include electrode portions that extend through a vessel and/or chamber wall, other exemplary leads include electrode portions that remain within the lumen of a vessel and/or within a chamber of the heart. In addition, referring to Fig. 7, similar leads are optionally used that may extend to pre-ganglionated field regions, ganglionated field regions and/or post-ganglionated field regions on, for example, the dorsal side of the heart. Again, such leads optionally extend to pre-ganglionated field regions, ganglionated field regions and/or post-ganglionated field regions associated with at least one of the seven subplexuses identified in the Pauza et al. reference. Further, exemplary leads optionally include electrode portions that remain within the lumen of a vessel and/or within a chamber of the heart.

**[0134]** Another exemplary method involves stimulation of afferent parasympathetic nerves. As already mentioned, the study by Kawada et al., "Vagosympathetic interactions in ischemia-induced myocardial norepinephrine and acetylcholine release", *Am. J. Physiol. Heart Circ. Physiol.*, 280:H216 - H221 (2001), reported that, in animals subject to occlusion of their left anterior descending coronary artery, a resulting increase in sympathetic activity was diminished by vagal afferent activity. In particular, vagal afferent activity reduced ischemia-induced myocardial norepinephrine release. An exemplary method optionally includes positioning of one or more electrodes, via a vein, proximate to an epicardial and/or endocardial vagal afferent nerve and delivering a stimulation pulse to the one or more electrodes to thereby stimulate the vagal afferent nerve. An exemplary device includes a lead having one or more electrodes positionable, via a vein, proximate to an epicardial and/or endocardial vagal afferent nerve and hardware and/or software configured to deliver a stimulation pulse to the one or more electrodes. The exemplary method and/or device optionally deliver a stimulation pulse postinspiration. A desirable effect of the exemplary method and/or device is to reduce myocardial norepinephrine release and/or concentrations, which, in turn, may allow parasympathetic tone to increase end diastolic volume and passive contractility.

**[0135]** According to such an exemplary method and/or device, one or more electrodes are positioned and/or positionable in an epicardial vein and/or chamber of the heart. In particular, one or more electrodes are optionally positioned proximate to an atrial vagal afferent nerve and/or a ventricular vagal afferent nerve. Further, during positioning, a variety of locations may be examined to determine which locations produces a more pronounced and/or desirable response.

**[0136]** Various exemplary methods optionally include positioning one or more electrodes in the superior vena

cava (SVC), the inferior vena cava (IVC) and/or the coronary sinus (CS). Various exemplary methods optionally include positioning one or more electrode in the azygous vein. Suitable electrode portions for positioning electrodes in or near a nerve and/or the heart include, but are not limited to, basket type or double helix type of electrode portions, see, e.g., U.S. Patent Application having Serial No. 10/321,307, filed December 16, 2002, entitled "Implantable lead and electrode portion", to Heland and Shelchuk, and U.S. Patent Application having Serial No. 10/000,333, filed October 22, 2001, entitled "Implantable lead and method for stimulation the vagus nerve", to Weinberg.

**[0137]** In various exemplary methods, parasympathetic stimulation aims to stimulate a parasympathetic nerve and to avoid producing an evoked response from the myocardium. In this regard, parasympathetic stimulation may occur according to a power, frequency, duty cycle, phase (e.g., monophasic, biphasic, triphasic, etc.) that reduces the risk of myocardial stimulation and/or parasympathetic stimulation may occur during a refractory period of the myocardium to reduce the risk of myocardial stimulation.

#### Determining Vagal Tone and/or Inspiration/Postinspiration

**[0138]** As already mentioned, Mendelowitz noted that "cardiac vagal neurons recorded in vivo receive inhibitory synaptic input during inspiration, which is then followed by a rapid depolarization caused by excitatory synaptic input during postinspiration". Therefore, for a variety of reasons, the aforementioned exemplary methods and/or device optionally stimulate parasympathetic nerves postinspiration, i.e., not during inspiration. Referring to Fig. 12, an exemplary method 1200 for delivery of one or more stimulation pulses postinspiration is shown. In a monitoring block 1204, a stimulation and/or other device monitors directly and/or indirectly heart rate. Next, in a detection block 1208, the stimulation and/or other device detects respiratory sinus arrhythmia. Following detection, in a determination block 1212, the stimulation and/or other device determines a period associated with inspiration. Next, in a delivery block 1216, the stimulation device delivers a stimulation pulse to a parasympathetic nerve. Also note that such a method can determine a patient's vagal tone.

**[0139]** In another exemplary method, a stimulation and/or other device monitors inspiration directly and/or indirectly through use of a ventilation module and/or sensor (e.g., impedance, etc.). In this exemplary method and the aforementioned method, parasympathetic stimulation pulse delivery during postinspiration only can decrease power demand on an implantable stimulation device. In yet another exemplary method, parasympathetic stimulation pulse delivery occurs during a refractory period to avoid stimulation of cardiac and/or other tissue. Of course, an exemplary combined method

optionally includes delivery of a parasympathetic stimulation pulse postinspiration in a refractory period.

#### Parasympathetic Stimulation Postinspiration and/or Synchronous with Heart

**[0140]** As already mentioned, parasympathetic stimulation may occur postinspiration (e.g., not during inspiration) and/or in synchrony with one or more cardiac events (e.g., events typically found in a cardiac cycle). Fig. 13 shows an exemplary method 1300 wherein parasympathetic stimulation occurs according to respiratory cycle and/or according to one or more events in a cardiac cycle. Various exemplary methods presented herein may implement one or more of the blocks or procedures described with reference to the exemplary method 1300.

**[0141]** A start block 1304 may occur at anytime an exemplary method desires to implement parasympathetic nerve stimulation. A decision block 1308 follows that determines whether a patient is in a postinspiration phase of a respiratory cycle. For example, an exemplary device may detect impedance, movement of an implanted device, pressure, cardiac characteristics, autonomic tone, etc., and then use such information to determine one or more phases of a respiratory cycle. In the exemplary method 1300, if the decision block 1308 determines that a patient is not in a postinspiration phase, then the method 1300 may continue in a wait block 1316, which either causes an appropriate delay or waits for an event indicative of a postinspiration phase. If the decision block 1308 determines that a patient is in a postinspiration phase, the method 1300 continues in a ventricular event detection block 1312; the wait block 1316 also continues at the ventricular event detection block 1312. In general, the ventricular event detection block 1312 aims to detect an R wave or a ventricular contraction. As described above, parasympathetic stimulation may act to increase end diastolic volume and indirectly to increase passive contractility via the Frank-Starling mechanism; however, parasympathetic stimulation is potentially detrimental to active contractility. Thus, according to the method 1300, it is desirable to avoid parasympathetic stimulation at a time in the cardiac cycle that may impair active contractility.

**[0142]** Upon detection of a particular event, the method 1300 then initiates parasympathetic stimulation in an initiation block 1320. The stimulation may continue for a set period of time, may continue until detection of another cardiac event or may continue for a certain amount of time based on detection of a subsequent cardiac event. As shown in Fig. 13, the method 1300 includes an atrial event detection block 1324. For example, such a detection block may detect an atrial paced event and/or an intrinsic atrial event. Upon detection of the atrial event, the method 1300 proceeds to set a timer to a fraction of an atrio-ventricular interval in a set timer block 1328. Upon expiration of the timer, a halt parasympa-

thetic stimulation block 1332 halts parasympathetic stimulation. In this example, parasympathetic stimulation is halted to ensure that the parasympathetic stimulation does not cause any significant detriment to active contractility. Thereafter, the exemplary method 1300 continues at the decision block 1308, at the detection block 1312 or at another suitable point (e.g., a decision block that decides whether further parasympathetic stimulation is required). Of course, as mentioned above, parasympathetic stimulation may be delivered during a refractory period of the myocardium (e.g., the myocardium proximate to one or more electrodes). Hence, the exemplary method 1300 optionally includes stimulating during a refractory period, for example, to reduce the risk of producing an evoked response from the myocardium.

#### Selecting and/or Positioning Leads and/or Electrodes

[0143] An exemplary method for selecting and/or positioning a lead and/or an electrode is optionally implemented during implantation and/or after implantation. For example, during an implantation procedure, a patient is optionally instrumented to monitor heart function. For example, heart rate may be monitored via an EKG and contractility via arterial pressure sensors (e.g., the time derivative of the pressure can provide a good measure of contractility). In this example, monitoring of cardiac function and/or other functions may occur through use of external instrumentation and/or through use of implanted leads and/or sensors.

[0144] Consider a situation wherein parasympathetic tuning via parasympathetic nerve stimulation aims to decrease heart rate, to increase end diastolic volume and/or to decrease AV conduction. In such a situation, an exemplary method includes adjusting pulse amplitude and/or pulse frequency to relatively high values, automatically or manually (e.g., an implantable device having a lead and/or electrode implantation, selection and/or positioning mode(s)). In this exemplary method, through use of stimulation pulses and monitoring of cardiac function and/or other functions, a lead and/or electrode is positioned during implantation to achieve an optimal and/or a satisfactory decrease in heart rate (e.g., an increase of therapeutic value), increase in end diastolic volume and/or decrease in AV conduction. In this exemplary method, for example, a physician may slowly move a lead throughout an appropriate region and deliver pulses until a desired decrease in heart rate, increase in end diastolic volume and/or decrease in AV conduction is seen maximally via monitoring.

[0145] In yet another exemplary method, a lead and/or an electrode are optionally positioned to decrease sympathetic activity while at the same time minimizing stimulation effects on heart rate. Once a "sweet spot" is found, then pulse parameters are optionally adjusted to minimize electrical power consumption, for example, by previously mentioned exemplary methods.

#### Conjunct to Sympathetic Blockade

[0146] Pharmacological approaches to blockade of the sympathetic system include inhibition of central sympathetic outflow (using central sympatholytics, e.g. rilmenidine, moxonidine), blockade of the catecholamine biosynthetic pathway (dopamine beta hydroxylase antagonists) and blockade of the cardiac effects of sympathetic activation (beta-adrenoceptor blocking agents), see, e.g., Krum, "Sympathetic activation and the role of beta-blockers in chronic heart failure", *Aust. NZ J. Med.*, 29(3): 418 - 427 (1999).

[0147] Beta-blockers aim to offset deleterious effects associated with sympathetic activity. However, a high beta blocker level may lead to bradycardia, symptomatic hypotension, excessive fatigue, and/or progressive signs or symptoms of congestive heart failure. Under such circumstances, beta blocker dose reduction is typically necessary and/or administration of an inotropic agent, see, e.g., Shaker and Bristow, "Low-level inotropic stimulation with type III phosphodiesterase inhibitors in patients with advanced symptomatic chronic heart failure receiving beta-blocking agents", *Curr. Cardiol. Rep.*, 3(3): 224 - 231 (2001). However, these methods inherently require human intervention, which may take days or weeks. Consequently, under such circumstances a need exists to reduce blockade or antisympathetic therapy in a more expeditious manner.

[0148] Thus, according to various exemplary methods and/or stimulation devices described herein, parasympathetic stimulation is used in patients subject to sympathetic blockade therapy. Under such circumstances, for example, a baseline blockade is provided through administration of an agent while a variable blockade is provided through parasympathetic stimulation. Parasympathetic stimulation includes afferent parasympathetic stimulation (e.g., to decrease release of norepinephrine) and/or efferent parasympathetic stimulation. Further, rather than adjusting beta blocker dosage, parasympathetic therapy can be adjusted. Indeed, use of such methods and/or devices can maintain at least some benefits of blockade while providing increased heart rate and/or inotropy when needed. In such patients, increased heart rate and/or inotropy are needed, for example, during times of physical exertion, including, but not limited to, sex. During such times, parasympathetic stimulation is, for example, diminished or halted.

#### **Claims**

1. Apparatus for improving heart performance, comprising:

means (106) for detecting a need for increased cardiac output; and  
responsive to the detecting, characterised in

that the stimulating means comprises means for stimulating (144) a parasympathetic nerve, to increase vagal tone and to increase end diastolic volume.

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2. Apparatus as claimed in Claim 1, **characterised in that** the means for detecting (104,106,108) comprises one or more sensors.

3. Apparatus as claimed in Claim 1 or Claim 2, **characterised in that** the stimulating means comprises an electrode (144) positionable proximate to the parasympathetic nerve.

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4. Apparatus for improving heart performance, comprising:

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means for detecting a need for increased cardiac output and stimulating means responsive to the detecting, **characterised in that** the means for detecting is arranged to detect a need to increase stroke volume; the stimulating means is arranged to stimulate a parasympathetic nerve, responsive to the detecting, according to one or more stimulation parameters to increase vagal tone and thereby to increase end diastolic volume; the apparatus also comprising means for determining whether adequate AV conduction exist, and means adjusting one or more of the stimulation parameters responsive to the determining.

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5. Apparatus for improving heart performance, **characterised by:** means for detecting an increase in sympathetic tone; means for stimulating a parasympathetic nerve according to one or more stimulation parameters; means for determining whether adequate AV conduction exists; and means for implementing ventricular pacing if inadequate AV conduction exists.

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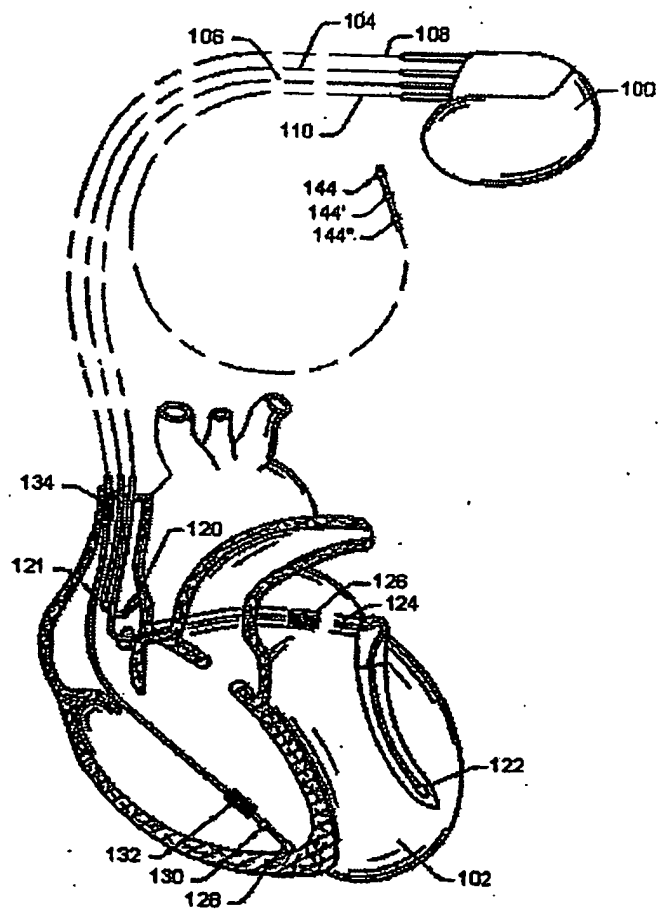


Fig. 1

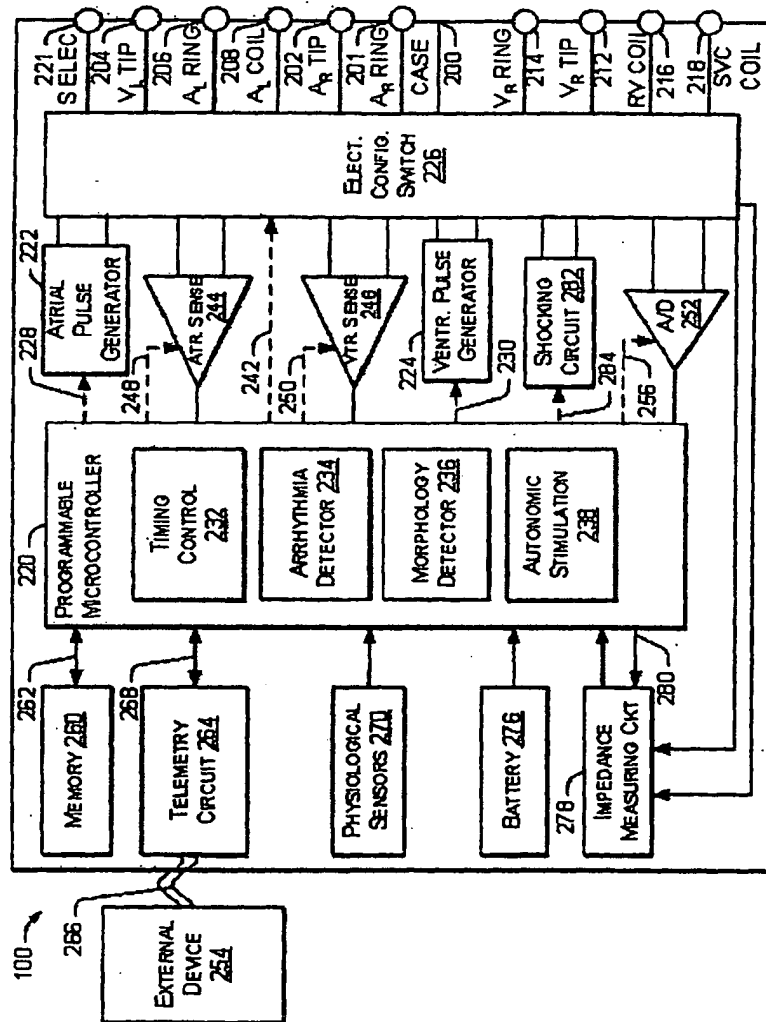
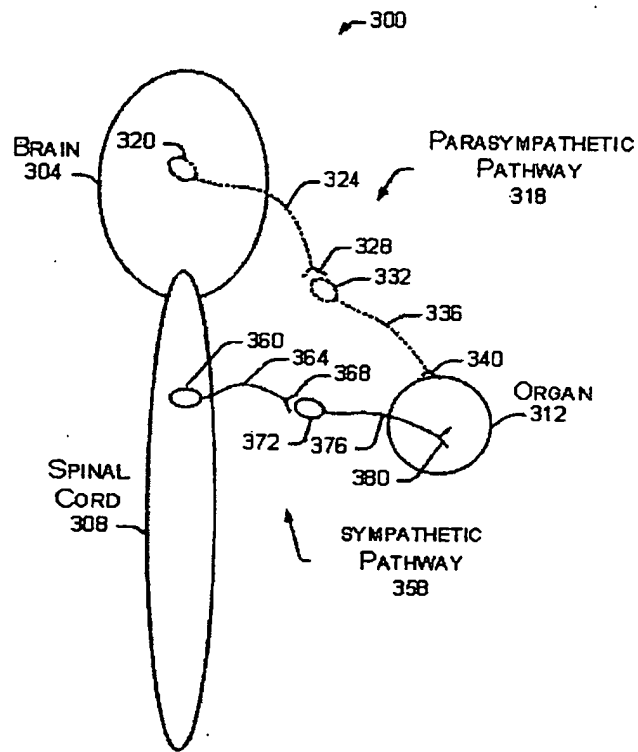
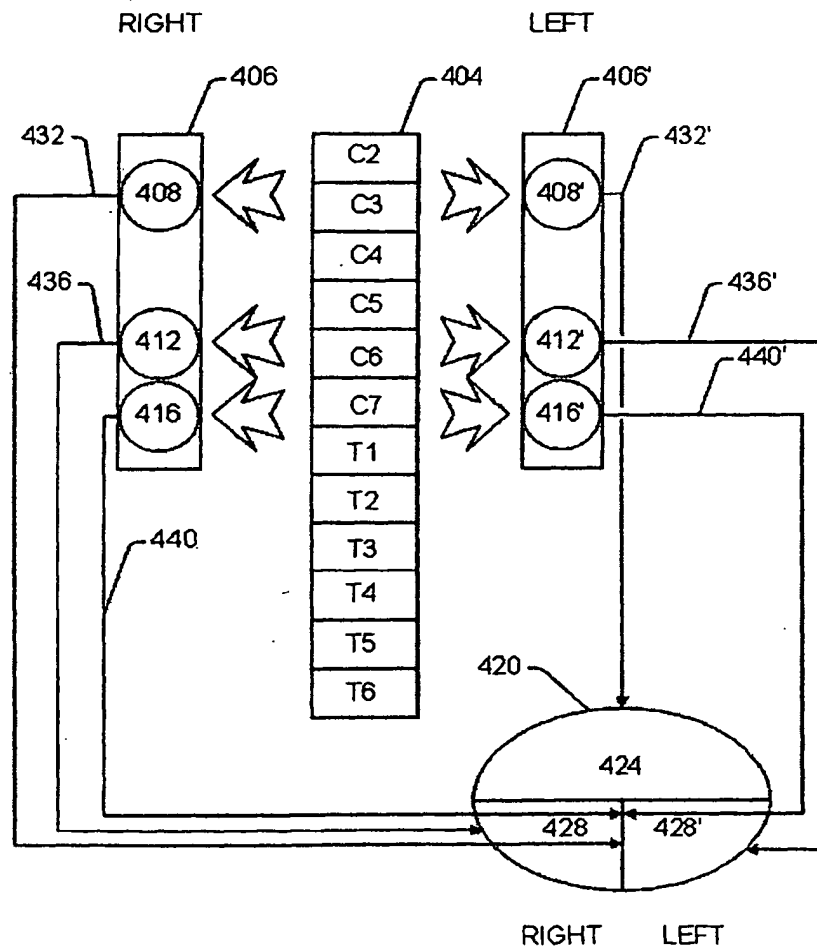


Fig. 2

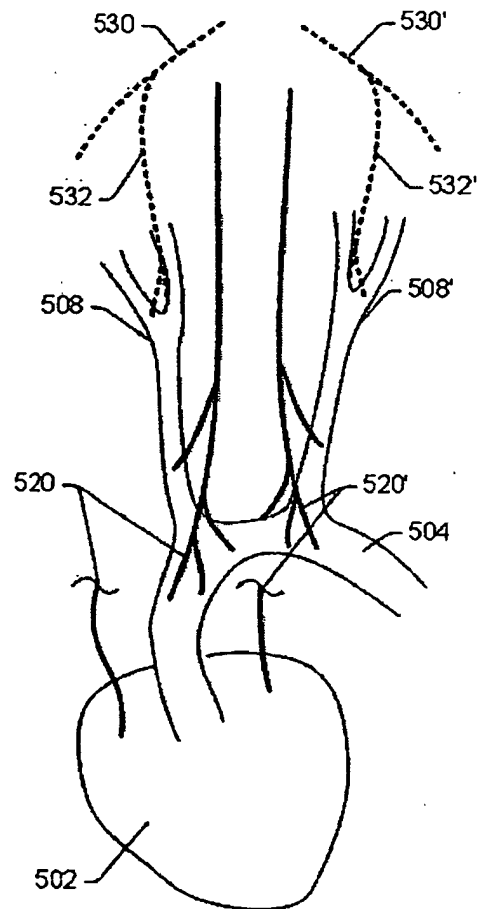


*Fig. 3*





*Fig. 4*



**Fig. 5**

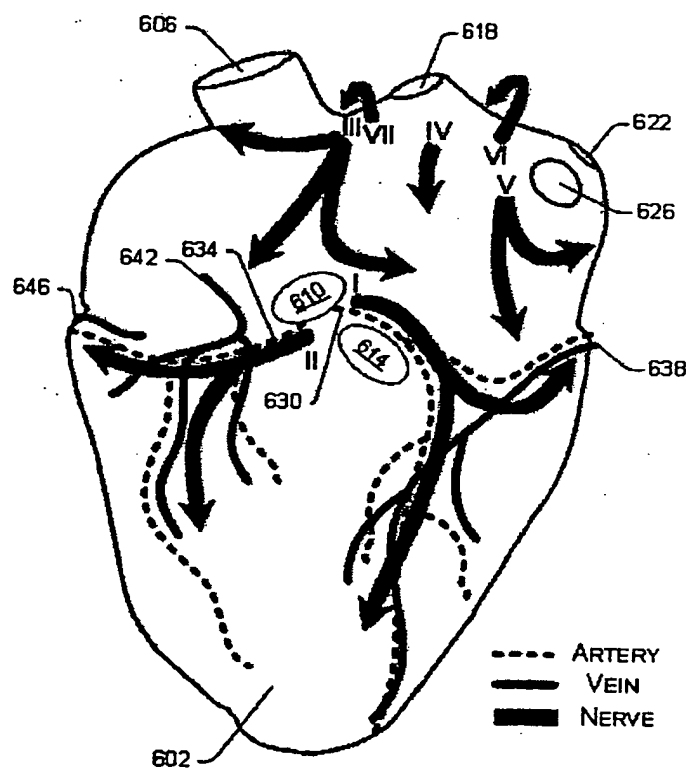


Fig. 6

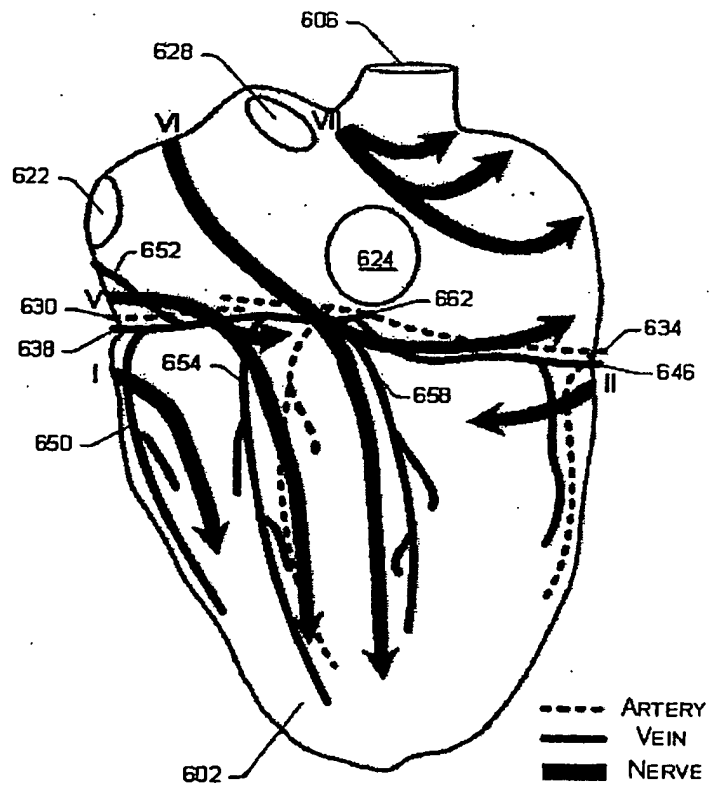
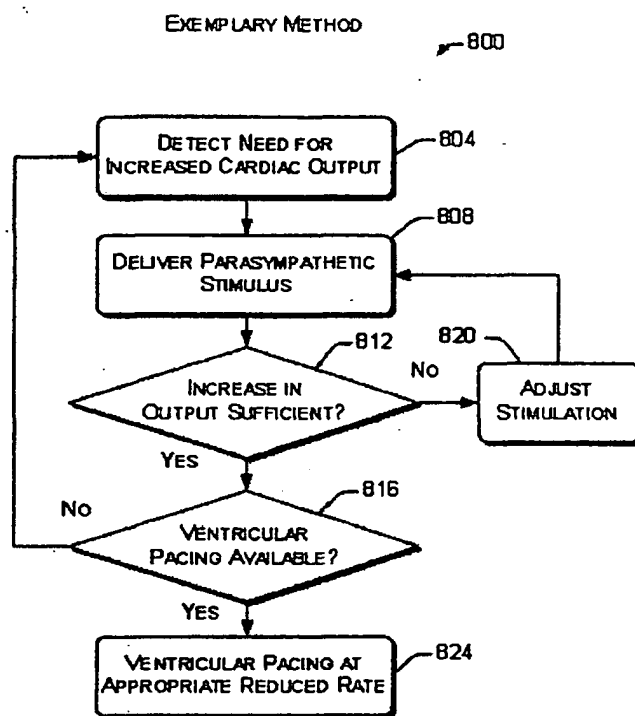
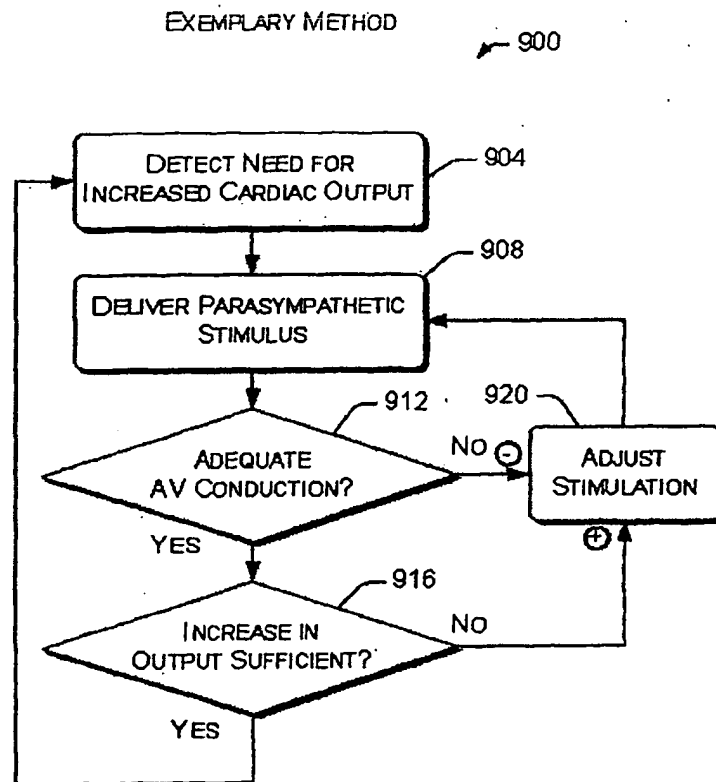
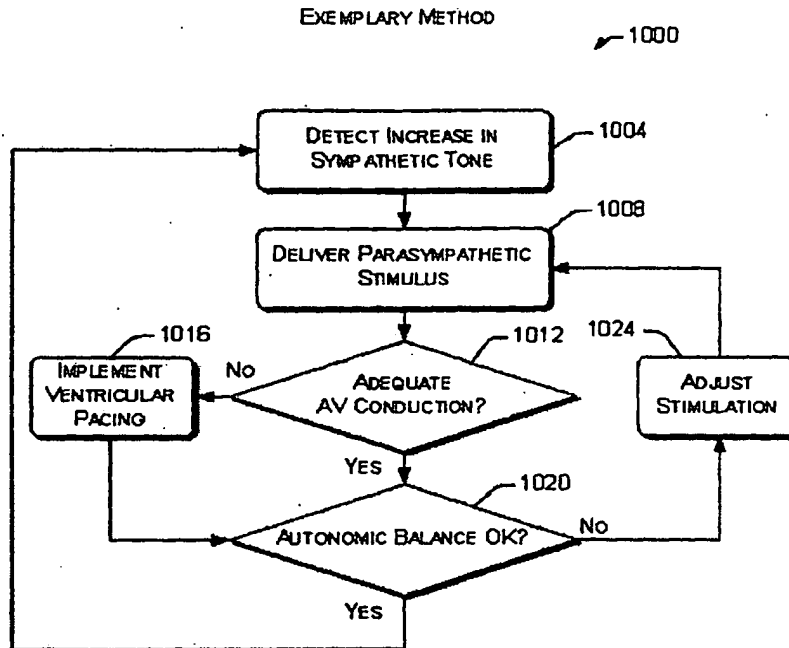
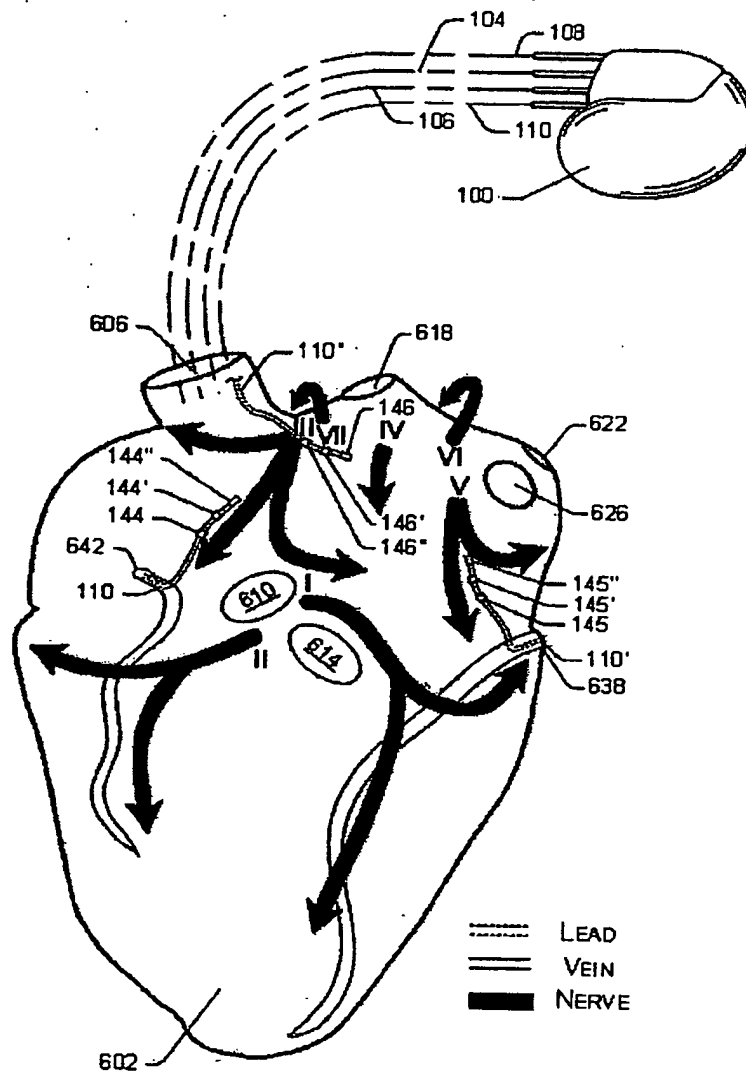


Fig. 7

*Fig. 8*

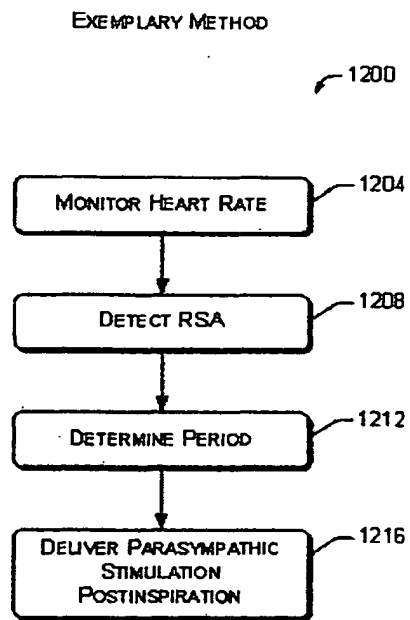
*Fig. 9*

*Fig. 10*

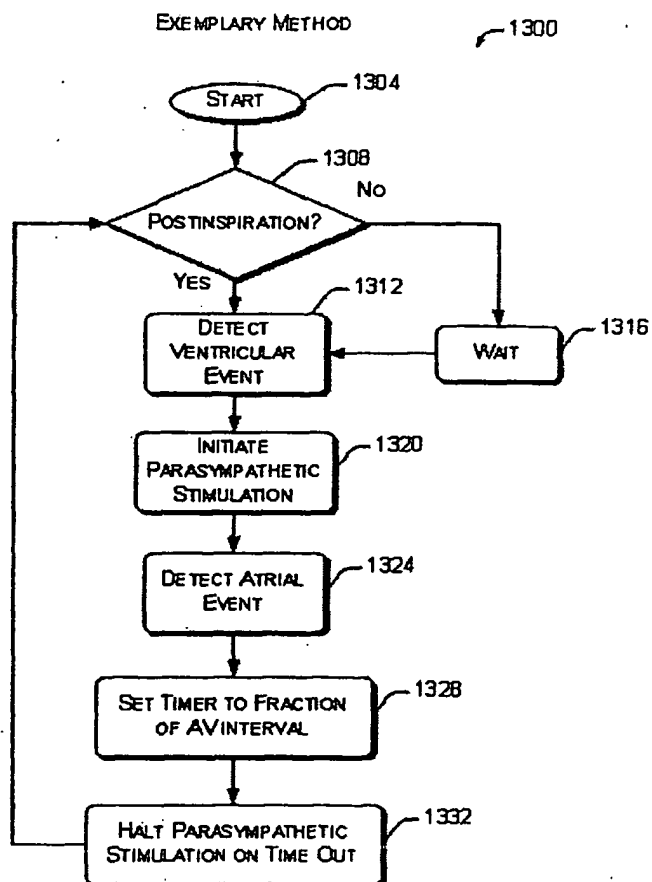


**Fig. 11**





*Fig. 12*

*Fig. 13*